TECHNOLOGICAL CHANGE IN U.S. AGRICULTURE: THE ROLE OF PUBLIC AND PRIVATE R&D

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Abstract

An endogenous growth model, in which technical change is attained through public and private R&D activities, is utilized to explore the role of technical change in TFP growth, to determine the impact of public and private agricultural R&D investments on the flow of agricultural patents, and to analyze the determinants of private agricultural R&D spending. The implications of the theoretical model are tested empirically for the U.S. agricultural sector. The empirical results are consistent with the theory. The main finding is that there is a positive relationship between TFP growth in the agricultural sector and agricultural patents. Current and past public and private R&D investments in agricultural sector have a significant and positive effect on agricultural patents. It is found that public R&D investment does not crowd out private R&D investment.

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1. Introduction

The performance of the U.S. agriculture during the postwar period is noteworthy. Agriculture has one of the highest productivity growth rates of all industries and productivity growth is a major source of total output growth. There has been a considerable amount of work dedicated to understanding the determinants of changes in the productivity level in the agricultural sector.

Different factors have been used in empirical studies to explain the changes in productivity. Some of these factors are public and private research & development activities, public infrastructure expenditures, extension activities, education and technical advances in material inputs. There have been a number of empirical studies that focused on the link between TFP and these factors to understand which are significant contributors in different states, for different agricultural commodities and for different time periods. Another motivation of this empirical literature has been estimating the rate of return to investments in agricultural R&D and extension.

Agriculture in the U.S has a history of public sector research & development that dates back to the second half of the 19^{th} century. The public sector has traditionally dominated R&D activities in agriculture, and was the main source of many innovations that helped farmers to increase their output. Private R&D activities in agriculture started much later, but real private R&D spending has surpassed real public R&D spending in the last two decades. Advances in the biotechnology sector and changes in the definition of property rights are cited as the main elements contributing to the increasing role of private R&D in agriculture.

This paper draws on endogenous growth theory to explore the role of technical change in TFP growth. The impact of public and private agricultural R&D investments on the number of agricultural patents is examined. An analysis of the determinants of private agricultural R&D investment is presented. These objectives are pursued on two grounds: theoretical and empirical.

In the theoretical part, a quality innovation model that explores the connection between TFP and technical change is employed. Technical change is modeled to be the result of commercially motivated efforts of private sector researchers responding to economic incentives and a public R&D sector. The model developed here makes a contribution to the existing literature on endogenous growth theory by incorporating a role for a public R&D sector through different channels. The public R&D sector helps the private R&D sector through subsidies and providing technical know-how; however it also may crowd out part of private R&D sector investment by competing with it when trying to come up with the next best technology. The level of private agricultural R&D investment is endogenously determined by the decisions of economic agents, whereas public R&D investment is taken to be determined exogenously. The quality innovation model not only describes a mechanism that shows how technical change leads to TFP increases, but also explores the liaison between public and private R&D sectors.

The empirical work based on this model has three objectives. The first is to measure and explain technical change. Technical change is defined as an increase in the total number of inventions available to producers, and therefore agricultural patent data are used as a proxy for technical change. A patent production function is estimated in which the explanatory variables are public and private R&D investments. The second objective is to test the implications of the model on the relation between technical change and TFP. The third is to explore the factors that determine private agricultural R&D investment. To pursue these objectives, a simultaneous system of equations is estimated with time series data for U.S. with three stage least squares, 1960-1996. The dependent variables are TFP, agricultural patents, and private agricultural R&D investment.

The empirical results are fairly consistent with the prior expectations based on the theory. The main finding is that there is a positive relationship between TFP growth in the agricultural sector and agricultural patents. Current and past public and private R&D investments in agricultural sector have a significant and positive effect on agricultural patents. Different factors have been identified from the theory that affect the private R&D investment decisions in agricultural sector. It is found that public R&D investment does not crowd out private R&D investment. Interest rate has a negative effect on private R&D investment, whereas price received by farmers has a positive effect. The sign of the TFP variable depends on the number of lags included in the estimation.

2. Changing Role of Public and Private R&D Sectors

Agricultural R&D activities in the U.S. have been historically dominated by the public sector. The public sector's involvement has been through a federal-state partnership. The federal government supports intramural research at USDA and funds extramural research at state institutions. The state system is composed of a joint research-teaching-extension mission carried out by State Agricultural Experiment Stations and land-grant universities. Federal-state system and extension services developed new technologies and encouraged their commercialization and adoption by farmers.

The economic rationale used to justify the government's intervention in R&D has been market failure. Because the knowledge acquired from some type of R&D activities is in a public good nature, private agents will not undertake the socially optimal level of R&D activity. If it is not possible to capture the benefits from their research, the private sector will invest too little in R&D, and therefore government has to make up for the discrepancy. As a result of this conceptualization, the division of labor between public and private R&D has traditionally been defined as the public sector concentrating on basic research (or pre-technology research) and the private sector concentrating on applied research and technology development (Agricultural Outlook (1999), Huffman and Evenson (1993a)).

However, recent developments in the agricultural R&D sector require rethinking the division of labor between public and private sector. The level and the composition of both public and private R&D

investment have changed. Public R&D investments stagnated after 1980s and decreased after mid 1990s in real terms. On the other hand, the level of private expenditures has increased dramatically and exceeded the level of public expenditures for the last two decades. Between 1960 and 1996, private R&D spending nearly tripled in real terms, whereas public R&D spending only doubled. While public R&D spending made 53% of total R&D spending in 1960, this ratio dropped to 44% in 1996. Hence, it could be said that private sector has become an equally, if not more, important part of the agricultural R&D activities for U.S.

The composition of public R&D spending and the sources of funds changed over time, as well. Federal funds for public R&D that includes funds for USDA intramural research and federal support for SAES became stagnant after 1980s and decreased after 1993. Federal funds given to state institutions are made up of two categories: formula funds and funds given to a project. Since the 1960s, the share of federal research dollars given as formula funds decreased, whereas share of project-oriented funds increased. State funds given to SAES and cooperating institutions also stagnated after 1980s and started decreasing after 1990s. Non-government funds given to public R&D institutions show a steady upward trend with a higher slope after the end of 1970s. These are mainly contributions from the private sector, mostly for research conducted at land-grant universities. In addition, allocation of public resources by goal shows some changes. The percentages of funds allocated to "management of natural resources" and to "protection of forests, crops and livestock from pests and disease" have increased respectively from 12% and 21% in 1973 to 15% and 24% in 1992. The ratio of funds allocated to "reduction of production costs of food and forest products" and "development of new products and enhancement of quality" decreased respectively from 32% and 12% in 1973 to 30% and 10% in 1992 (Fuglie et al. (1996)).

The categories of private R&D investment changed over time too. Expenditures on "plant breeding", "agricultural chemicals" and "veterinary pharmaceuticals" as a ratio of private R&D spending increased, whereas the ratio of research spending on "farm machinery" and "food and kindred products" decreased in total private R&D spending. Particularly in plant breeding R&D, the trend has been toward greater private sector investment. Heisey et al. (2001) reports that there is a significant increase in plant breeders in private sector for crops such as maize, sorghum, cotton and soybean, whereas public sector breeders declined over the same period. There has also been a notable shift from planting of public sector varieties to private sector varieties for soybeans and cotton over the past 20 to 40 years.

Different factors have been identified as possible reasons for the increasing role of private sector in agricultural R&D. It has been argued that improvements in the biotechnology sector and strengthened patent protection for biological inventions helped private firms find new sources of profit from agricultural R&D, and secure better returns from their investments.

Patent protection has been available for agricultural R&D products for a long time. However, in the last three decades the scope and the strength of patent protection laws have expanded. The Plant Variety Protection Act of 1970 provided intellectual protection for developers of sexually reproduced plants other than hybrids. With this act, USDA started granting Plant Variety Protection Certificates. The 1995 Supreme Court decision to restrict a farmer's right to resell protected seeds has transformed these protection certificates into utility patents. Another major development in this area was the 1980 Supreme Court decision that made it possible to acquire intellectual property protection for living organisms. In 1985 U.S. Patent and Trademark Office began granting utility patents to new types of plants and plant parts, and also to animal genes and new and unique breeds of non-human animals. Although, the rate of patent application and patent granting for biological inventions increased after these developments, the evidence regarding the impact on different sectors have been mixed. One sector of private R&D for which the effect of intellectual property rights is noticeable is plant breeding. Before IPR's, plant breeders in private sector concentrated most of their efforts on 'hybrid seed' technology, such as maize, sorghum, and sunflowers. 1970 PVPA gave protection for new varieties of sexually reproduced seed crops other than hybrids. With protection to new varieties private seed companies have expanded their research efforts toward new areas. Butler and Marion (1985) report that PVPA encouraged development of new varieties of soybeans and wheat, but did not affect public sector crop breeding. Alston and Venner (2000) report that PVPA contributed to higher investment by SAES in developing new wheat varieties, but private sector efforts in developing non-hybrid wheat varieties had not increased.

At this point, it is necessary to note that intellectual property protection is also available to public sector discoveries. In 1980, the Bayh-Dole Patent Policy Act has permitted individuals and institutions to obtain patents and then grant licenses for the research results that have been conducted with Federal funds. Cooperative Research and Development Agreements have been set up as a mechanism through which public and private institutions can collaborate. Public R&D institutions have applied for patent protection but only to a limited extent. Particularly, SAES units regarded application for patents to be in conflict with their public institution status. USDA generally sought patents for its inventions and made them available for nonexclusive licensing. The SAES-USDA system has generated far fewer IPR protected inventions per dollar expended on research than private sector (Huffman and Evenson (1993a)).

All these changes in the nature and amount of private and public R&D investment have generated a need to find a new way to analyze the division of labor between public and private R&D sectors. As private R&D firms have gained the ability to appropriate benefits from their own research, the rationale for government intervention in terms of providing the socially optimal amount of research is weaker. An example of this is plant breeding R&D for crops such as maize, sorghum, soybeans and cotton, where private sector is gaining more responsibility. For such R&D activities, public sector may lead to "crowding out" of private sector. However, there are other areas where the role of public sector may still be needed. One of the items has been identified as providing access to the knowledge created by private firms for the whole society to benefit. Another role is defined by Huffman and Evenson (1993a), who claim that applied technology can be done by private sector, but this still depends on 'basic science'. For that reason, it is argued a public sector role is still needed for basic science research. A role for public sector still exists for research in areas that private sector may not find profitable but is crucial for society. Other similar public roles are research in minor crops, germplasm preservation and development, education of R&D personnel and farmers, environmental and food safety regulations and extension activities.

The model employed in this study can be used to evaluate the relation between public and private R&D sectors. In this model, both public and private sector conduct R&D. The motivation of private sector research is the compensation of successful innovators. Property rights over the production and sale of R&D products are necessary to secure the reward from innovation. The recent institutional developments in the U.S. provides a basis for using a model where a market for the products of R&D sector exist and R&D firms have patent protection over their research results. The model incorporates two roles for public sector. The first role for public sector is to conduct R&D to create higher quality intermediate inputs, same as the private R&D sector. Therefore, public and private R&D sectors are competing with each other. The second role for public sector is to complement the private sector. This role is incorporated into the model in the form of a subsidy equivalent to private R&D firms that effectively lowers their cost. The rationale for this cost decrease stems from the fact that many public R&D activities' results are made publicly available. This flow of knowledge may help private firms and decrease their costs. The net effect of the public sector activities on private sector is ambiguous in the theoretical model.

3. Previous Literature on the Analysis of the Impacts of Research

Public and private research investments and extension activities have been cited as the primary source of U.S. agricultural TFP growth. There has been a rich literature starting with the work of Griliches that attempted to measure the impact of research and extension activities on Total Factor Productivity and agricultural output. These studies have reported positive and high rate of returns from R&D activities. These rates of return range from 0 percent to 300 percent and differ according to the study period, the agricultural commodity, and the methodology used. To give a brief summary, Huffman and Evenson (1993a) estimate an internal rate of return of 41 percent for public R&D and 46 percent for private R&D for the period 1950-82. Chavas and Cox (1992) use a non-parametric approach and estimate an IRR of 28 percent for public R&D and an IRR of 17 percent for private R&D for the same period. Makki, Thraen and Tweeten (1999) report an IRR of 27 percent for public R&D and 6 percent for private R&D using a cointegration and error correction model framework for the period 1930-1990. A more complete list of studies on this topic can be found in Fuglie et al. (1996). A meta-analysis of returns to agricultural R&D based on a comprehensive data set of previous studies were conducted by Alston, Marra, Pardey and Wyatt (2000). Their aim was to account for the large differences in estimated rates of return. They find that the type of research evaluated and the choice of lags partly explain the wide disparity among estimated rates of return.

In the empirical literature, different methods for analyzing the impacts of agricultural research investments have been used. These approaches can be categorized as parametric, non-parametric, and index number approaches. The parametric approach relies on a specific functional form that links inputs to outputs. Either primal, dual or single supply equation methods can be employed. With the primal method, a production function, a response function, or productivity function is estimated in the first stage. In the second stage, some behavioral assumptions are imposed on that model to infer the supply response to R&D. In the dual approach, a profit or a cost function is estimated in the first stage. Then, the derivative properties of the cost or profit function are used to derive the supply response. With single equation supply models, the supply response is estimated directly in one step. Non-parametric approaches avoid the use of functional forms and check the data for consistency with axioms of rational producer behavior. In the index number approach, aggregate measures of inputs or outputs are constructed with different indexing procedures. A Total Factor Productivity index is then constructed and used to assess the impacts of research.

There have been numerous studies that attempted to explain technical change in the agricultural sector. Hayami and Ruttan (1985) develop a theory of induced innovation that tries to incorporate technical change as a process that is endogenous to the economic system. They identify the conditions of factor supply and product demand as the venues for technical change. Griliches (1988) also observes that the level and rate of adoption of new agricultural techniques respond to economic incentives. He claims that variations in adoption could be explained by variables that represent the profitability of such adoptions. He also notes that “the criterion for public financing is social return on a project, while privately financed R&D will be only pursued to the extent that the developer of new ideas can capture some fraction of benefits”.

This study is in line with the previous work on technical change in the agricultural sector in the sense that it employs a R&D based endogenous growth model that describes technical change to be the result of commercially motivated efforts that respond to economic incentives. R&D sector undertakes the task of increasing the quality of intermediate goods, the result being a technical change. In this model, R&D sector is not exogenous but rather an integral part of the economy with a rather certain objective of profit making and a well-defined production activity. The model also establishes a simultaneous relation between R&D investments and TFP in the agricultural sector. In the equilibrium, not only public and private R&D have an impact on TFP, but also TFP affects private R&D investment. Since R&D sector is critical to the process of technical change, the economics determining R&D investment is analyzed theoretically in this model, as well. Private R&D investment depends on the economic conditions and the technical know-how in the economy. This shows that, while estimating the impact of R&D on TFP, the simultaneous relation between TFP and R&D investments needs to be considered. Otherwise, the parameter estimates may be inconsistent. That may be one of the reasons why the estimated rates of returns to research are much higher than the observed market rates of return on alternative investments.

4. Technical Change in Neoclassical Growth Models

Measures of productivity have been used extensively to analyze the process of growth and technical change and to explain its sources. In this respect, it is crucial to understand the definition of TFP in a neoclassical growth model as a proxy for technical change. In a neoclassical growth model, short run growth is driven by capital accumulation, but capital gives way to diminishing returns in the long run. Therefore, in the long run productivity growth is only due to exogenous technical progress. This is in contrast to endogenous growth models that endogenize the rate of technical progress. Productivity growth can continue indefinitely, either by avoiding diminishing returns to capital, or by explaining technical change as a result of optimizing behavior of economic agents. Neoclassical analysis provides us a measure of technical change in the form of TFP, and endogenous growth theory provides us different explanations of sources of technical change.

TFP is used as a measure of technical change based on certain assumptions such as competitive factor markets and Hicks neutral technology. The production function is $Y = A \cdot X_L^{\alpha} \cdot X_K^{1-\alpha}$ where Y is output, X_L is labor input and X_K is capital input. TFP is defined as $TFP = \frac{Y}{X_L^{\alpha} \cdot X_K^{1-\alpha}} = A$. The growth rate of TFP is $T\dot{F}P = \dot{Y} - \left[\alpha \cdot \dot{X}_L + (1-\alpha) \cdot \dot{X}_K\right]$. TFP is the name given to the difference between growth rate of output and share weighted growth rates of inputs. Caution should be employed when using TFP as a measure of technical change as TFP measures not only the impact of technical change but also other features that raise output growth beyond the measured contribution of inputs such as imperfectly competitive markets, increasing returns to scale, externalities, spillovers etc. In other words, if the assumptions employed in a neoclassical growth model do not hold, there will be biases between measured TFP growth and the TFP growth in the economy.

Jorgenson and Griliches (1995) attempt to develop better measures of inputs and outputs to reduce the magnitude of measured TFP. They claim that there are significant errors of measurement when data on growth of real product and real factor inputs is compiled, therefore biases in TFP measurement may occur. As TFP is the unexplained residual in this equation, accurate measurement of output and input growth will lead to a lower TFP estimate. An ideal productivity index is one that takes the value of one in all circumstances, i.e. all changes in the output are explained by the changes in inputs. In their study, they eliminate aggregation errors and correct for changes in the rates of utilization of labor and capital stock. They show that before these corrections, rate of growth of input explains 52.4% of the rate of growth of output, whereas after the corrections it explains 96.7% of the rate of growth of output. Although, Jorgenson and Griliches (1995) are correct in their claim that a correct index number framework and more accurate measurement of inputs would reduce the role of "residual" in accounting for observed growth in output, this line of thinking reduces the problem only to an empirical question of measuring productivity growth. Adopting such an approach ignores the issue of explaining the sources of technical progress and TFP growth. A complete analysis of technical change requires a unified approach that not only employs a correct measure of technical change but also offers an explanation of origins of technical change. In other words, we need to ask two questions at the same time: 'What happens?' and 'Why does it happen?' To answer the second question, an endogenous growth model that offers an explanation of how technical change occurs need to be employed.

5. Quality Innovation Model

The quality innovation model used in this study is partly based on an R&D based endogenous growth model and modified according to the characteristics of the U.S. agricultural sector. It entails a separate R&D sector, which is one of the sources of technical progress. The R&D sector is composed of two parts, a private sector and a public sector. Public and private R&D sectors lead to technical progress through improvements in the quality of intermediate goods used in the production of final good, which is agricultural sector output. The second source of technical progress is attained through increases in the human capital of farmers in the agricultural sector. This is modeled to be a function of extension services. The model is based on Barro and Sala-I-Martin (1995, Chapter 7), Grossman and Helpman (1991, Chapter 4) and Aghion and Howitt (1992).

Quality innovation model characterizes technical progress in the form of continuing series of improvements and refinements of existing goods and techniques rather than basic innovations that amount to dramatically new kinds of goods and methods of production[1]. When we look at the developments in the agricultural production process in the U.S., we see examples of the technical change that can be modeled by a quality innovation model. Use of hybrid seeds, adoption of improved livestock breeding practices, more effective agricultural chemicals, fertilizers and pesticides are examples of higher quality intermediate inputs.

Agricultural output is modeled as a final good that is produced with labor, land and N different

[1]The second type of technological progress is explored in a variety innovation model in which new goods and production processes are invented. Introduction of tractor to agricultural production is a rather dramatic change in the production process as a new intermediate good is introduced and it would be an example for a variety innovation model.

types of intermediate goods. The production technology assumed here disaggregates capital into a finite number of distinct types of producer durables (indexed by $j = 1 \ldots N$). Each intermediate good has a quality ladder along which improvements can occur. Improvements are conducted on the best available technology and are the result of research efforts of private R&D firms and public R&D sector. The model is set up with the assumption that a higher quality product is a perfect substitute for its lower quality counterpart. That is, in equilibrium only the highest quality intermediate goods are produced by R&D sector and used by final good producers to generate output[2].

Both public and private sectors conduct research aimed at improving the quality of intermediate goods and earn a property right over their research success. When a private R&D firm is successful in upgrading an intermediate good, it gains a monopoly right over the production and use of its product and 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 innovated the previously highest quality intermediate good. So, the success of an innovator, whether public or private sector, terminates the profit flow to the previous private sector innovator. The duration of the profit flow is random, as it depends on the uncertain outcomes of research efforts. The expected profit flow and the duration of this profit flow determine the equilibrium level of R&D investment.

Final good is produced in a competitive market, and the production function is

$$Y = A(E) \cdot L^{1-\alpha-\beta} \cdot H^{\beta} \cdot \sum_{j=1}^{N} \left(\tilde{X}_j\right)^{\alpha} \qquad (1)$$

where $0 < \alpha < 1$, $0 < \beta < 1$, $0 < \alpha+\beta < 1$, Y is agricultural output, L is land input, H is labor input and $\tilde{X}_j$ 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. Output is written as an additively separable function of all different types of capital goods. The additively separable form for the $\left(\tilde{X}_j\right)^{\alpha}$ implies that the marginal product of intermediate good $X_{j\kappa_j}$ is independent of the quantity employed of intermediate good $X_{l\kappa_l}$ where $j \neq l$. Therefore, one additional dollar of a capital good has no effect on the marginal productivity of another capital good[3].

A(E) is the other component of technology available to final good producers. It is modeled as a

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[2] Instantaneous adoption of new technology is assumed.

[3] If $Y = A(E) \cdot L^{1-\alpha-\beta} \cdot H^{\beta} \cdot (\sum_{j=1}^{N} q^{\kappa_j} \cdot X_{ij\kappa_j})^{\alpha}$, then $MP(X_{j\kappa_j}) = A(E) \cdot L^{1-\alpha-\beta} \cdot H^{\beta} \cdot \alpha \cdot q^{\kappa_j} \cdot \left(1 \Big/ (\sum_{j=1}^{N} q^{k_j} \cdot X_{j\kappa_j})^{1-\alpha} \right)$.

function of activities that increase the human capital of farmers. These activities include extension services that help farmers adopt new technology and education of farmers.

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_j, then the available quality grades of an intermediate good are $1, q, q^2, q^3, ..., q^{\kappa_j}$. The quality-adjusted input from sector j can be written as $\widetilde{X}_j = \sum_{k=0}^{\kappa_j} q^k . X_{jk}$ when κ_j is the highest available quality. Same intermediate goods with different quality rungs are perfect substitutes for each other.

When only the highest quality goods are produced and used in equilibrium, the production function is

$$Y = A(E) \cdot L^{1-\alpha-\beta} \cdot H^{\beta} \cdot \sum_{j=1}^{N} (q^{\kappa_j} \cdot X_{ij\kappa_j})^{\alpha} \tag{2}$$

The private sector researcher who innovates the κ_j th quality of intermediate good j will accrue his profits until a new researcher comes up with the (κ_j +1)th quality of intermediate good j. The profit earned by the researcher from the latest innovation will be only through an interval of $T_{j\kappa_j} = t_{\kappa_j+1} - t_{\kappa_j}$, when κ_j is the best available quality (t_{κ_j} is the time when the κ_j th innovation occurs and t_{κ_j+1} is the time when (κ_j +1)th innovation occurs). This duration is random, as it depends on the uncertain outcomes of research efforts by both R&D sectors.

There are two separate sectors in this economy that pursue profit maximization. The first sector is the final good sector, which is set up in a perfectly competitive market. Final good producers maximize profits by taking land rental, wage rate, price of intermediate inputs and price of agricultural output as given and by choosing L, H and $X_{ij\kappa_j}$. Their profit maximization problem is

$$\max_{L,H,X_{j\kappa_j}} \pi^{FG} = P_Y \cdot Y - i \cdot L - w \cdot H - \sum_{j=1}^{N} P_{j\kappa_j} \cdot X_{j\kappa_j} \tag{3}$$

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

The second sector is the monopolistically competitive private R&D sector. The successful private researcher gains a monopoly right to produce and sell that higher quality intermediate good. The marginal cost production of intermediate good is 1 for all qualities. The monopolist producer of the intermediate

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Then $X_{j\kappa_j}$ can not be determined separately from other intermediate goods. With such a production function, total capital is defined as being proportional to sum of all different types of capital, i.e. all capital goods are perfect substitutes.

good with quality level κ_j will choose the price P_j to maximize its profits. The profit maximization problem for a private researcher is

$$\max_{P_{j\kappa_j}} \pi^{RD} = (P_{j\kappa_j} - 1) \cdot X_{j\kappa_j} \tag{4}$$

From this optimization, the price for every intermediate good is derived as $P_j = P = 1/\alpha$, which is constant across sectors and over time. This price exceeds marginal cost.

The quantity produced of j[th] intermediate good is derived by using the above two optimization problems as

$$X_{j\kappa_j} = P_Y^{1/(1-\alpha)} \cdot A(E)^{1/(1-\alpha)} \cdot L^{(1-\alpha-\beta)/(1-\alpha)} \cdot H^{\beta/(1-\alpha)} \cdot \alpha^{2/(1-\alpha)} \cdot q^{\kappa_j \cdot \alpha/(1-\alpha)} \tag{5}$$

To show that only leading edge quality intermediate goods are produced and used in equilibrium, we need to look at the pricing of different qualities of the same intermediate good. Each unit of a leading edge intermediate good is equivalent to **q** units of the next best good. If $P_{j\kappa_j}$ is the price of highest available quality intermediate good, then $(P_{j\kappa_j}/q)$ is the price of the next best available intermediate good. Then, the prices of an intermediate good with different qualities are ranked as follows: $(1/\alpha), (1/\alpha \cdot q), (1/\alpha \cdot q^2)...$ If $(1/\alpha \cdot q) < MC = 1$, then the next best producer will not be able to compete against the leader's monopoly price. In other words, if $\alpha \cdot q > 1$, then monopoly pricing will prevail. So, if **q** is large enough, then lower grades will be driven out of the market[4]. Only the best available quality of each intermediate good is produced and used[5].

The equilibrium level of agricultural output is derived as

$$Y = \sum_{j=1}^{N} q^{\kappa_j \cdot \alpha/(1-\alpha)} \cdot A(E)^{1/(1-\alpha)} \cdot P_Y^{\alpha/(1-\alpha)} \cdot L^{(1-\alpha-\beta)/(1-\alpha)} \cdot H^{\beta/(1-\alpha)} \cdot \alpha^{2\alpha/(1-\alpha)} \tag{6}$$

If an aggregate quality index is defined as $Q = \sum_{j=1}^{N} q^{\kappa_j \cdot \alpha/(1-\alpha)}$, then agricultural output is

$$Y = Q \cdot A(E)^{1/(1-\alpha)} \cdot P_Y^{\alpha/(1-\alpha)} \cdot L^{(1-\alpha-\beta)/(1-\alpha)} \cdot H^{\beta/(1-\alpha)} \cdot \alpha^{2\alpha/(1-\alpha)} \tag{7}$$

Technical change in the equation 7 is attained through increases in $Q \cdot A(E)^{1/(1-\alpha)}$. It is divided into two parts: Q and $A(E)^{1/(1-\alpha)}$. Quality index increases with efforts of public and private R&D sector trying to come up with the next higher quality intermediate good. The next step is to analyze the determinants of changes in this quality index. To do so, we need to look at what determines the incentive to innovate by private R&D firms and the role of public sector R&D in this process. The κ_j^{th} innovator

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[4] If $\alpha \cdot q < 1$, then the limit pricing strategy employed in Grossman and Helpman (1991) can be followed with the same result. Either way, the price of intermediate good is a mark-up over the marginal cost of production.

increases the quality of intermediate input X_j from $q^{\kappa_j - 1}$ to q^{κ_j}. This innovation can be either done by public R&D sector or by any private R&D firm. The private R&D firm prices its product and sells it through a finite interval, $T_{j\kappa_j} = t_{j\kappa_j+1} - t_{j\kappa_j}$. This duration depends not only on the efforts of private R&D firms but also the efforts of public R&D sector. Public R&D sector is not driven by the profit motive. Only private sector has monopoly profit accruing from its research successes. The present value of the monopoly profit for a successful private R&D firm is $V_{j\kappa_j} = \pi_{j\kappa_j} \cdot \frac{(1-e^{-r \cdot T_{j\kappa_j}})}{r}$ where r is the interest rate.

As each R&D success is random, technical progress will occur unevenly in one sector. Quality of an intermediate good will jump discretely once in a while by a multiple of **q**, when a private R&D firm or public R&D institution is successful. The size of this jump is given as **q**, but the time that this jump occurs is random.

Let p^* be the probability per unit of time of an increase from κ_j to (κ_j+1). This is the society's probability of innovation. This value equals to the sum of the probability of innovation by public sector, p^P, and the probability of innovation by private sector, $p^Z_{j\kappa_j}$. The duration of monopoly profits for private R&D firm is determined by p^*, not $p^Z_{j\kappa_j}$. Cumulative density function of p^* is $G(\tau) = 1 - e^{-p^* \cdot \tau}$ and the probability density function of p^* is $g(\tau) = p^* \cdot e^{-p^* \cdot \tau}$. The expected value of the next innovation to a private R&D firm is derived using the probability density function of p^* as $E(V_{j\kappa_j}) = \frac{\pi_{j\kappa_j}}{r + p^*}$. This value is the expected reward from making the κ_j^{th} innovation by a private R&D firm. Note that this value is lower than an expected value derived using only private sector's probability of innovation ($E(V_{j\kappa_j}) = \frac{\pi_{j\kappa_j}}{r + p^Z_{j\kappa_j}}$), as $p^* > p^Z_{j\kappa_j}$. 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[6].

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_j, is denoted as $Z_{j\kappa_j}$. As $Z_{j\kappa_j}$ increases, the probability of successful innovation per unit time in that sector by a private R&D firm increases. The

[5] Otherwise, there is no closed form solution for X (intermediate goods) and Y(output).

relation between $p^Z_{j\kappa_j}$ and $Z_{j\kappa_j}$ is defined in a linear relationship as

$$p^Z_{j\kappa_j} = Z_{j\kappa_j} \cdot \phi(\kappa_j) \tag{8}$$

The second term $\phi(\kappa_j)$ is added to reflect the complexity of a research project. κ_j is the total number of innovations in sector j and it is a proxy for the level of technology in that sector. As κ_j increases, it will be harder for R&D firms to come up with a new idea. Therefore, $\partial\phi(\kappa_j)/\partial\kappa_j < 0$ and $p^Z_{j\kappa_j}$ decreases as κ_j increases. In this model, it is assumed that p^* and $p^Z_{j\kappa_j}$ follow a Poisson process.

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

The prize for successful research is the basic determinant of private R&D effort. The expected reward from pursuing the $(\kappa_j + 1)^{\text{th}}$ innovation will be $p^Z_{j\kappa_j} \cdot E(V_{j,\kappa_j+1})$. The expected flow of 'net' profit from research in a sector that is currently at quality rung κ_j is $\Pi_{j\kappa_j} = p^Z_{j\kappa_j} \cdot E(V_{j,\kappa_j+1}) - Z_{j\kappa_j}$.

Assuming free entry into the research business, the society's rate of return from research is derived as

$$r + p^* = \phi(\kappa_j) \cdot q^{(\kappa_j+1)\cdot\alpha/(1-\alpha)} \left(1 - \alpha/\alpha\right) P_Y^{1/(1-\alpha)} \cdot A(E)^{1/(1-\alpha)} \cdot L^{(1-\alpha-\beta)/(1-\alpha)} \cdot H^{\beta/(1-\alpha)} \cdot \alpha^{2/(1-\alpha)} \tag{9}$$

κ_j enters into the rate of return equation in two ways. The rate of return increases as κ_j and $q^{(\kappa_j+1)\alpha/(1-\alpha)}$ increases. The rate of return decreases as κ_j increases and $\phi(\kappa_j)$ decreases. This is because the innovations in a sector are increasingly difficult. If the first effect dominates, the more advanced sectors will grow faster. The growth rate of the agricultural sector will rise over time. If the second effect dominates, the more advanced sectors will grow slower. Then, the growth rate of agricultural sector will fall over time. If 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. This way, R&D exhibit constant returns. In the rest of the solution, it will be assumed that these two forces offset each other.

In order to have $r + p^*$ constant across different sectors, the functional form for $\phi(\kappa_j)$ is assumed to be $(1/s \cdot \zeta) \cdot q^{-(\kappa_j+1)\cdot\alpha/(1-\alpha)}$. This definition is consistent with the previous assumption of $\phi'(\kappa_j) < 0$. The parameter $\zeta > 0$ represents the cost of research: a higher ζ lowers the probability of success for given

[6] That is why public sector may crowd out private sector.

values of $Z_{j\kappa_j}$ and κ_j. **s** takes a value between 0 and 1. This is another channel through which public sector activities enter into 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, the sunk cost of research for private R&D firms. This way, public R&D sector is a complement to private R&D sector.

The society's rate of return from research is derived in equilibrium as

$$r + p^* = (1/s \cdot \zeta)\left(1-\alpha \big/ \alpha\right) P_Y^{1/(1-\alpha)} \cdot A(E)^{1/(1-\alpha)} \cdot L^{(1-\alpha-\beta)/(1-\alpha)} \cdot H^{\beta/(1-\alpha)} \cdot \alpha^{2/(1-\alpha)} \quad (10)$$

The private sector's rate of return from research is derived by subtracting the public's probability of innovation from society's rate of return as

$$r + p^Z = (1/s \cdot \zeta)\left(1-\alpha \big/ \alpha\right) P_Y^{1/(1-\alpha)} \cdot A(E)^{1/(1-\alpha)} \cdot L^{(1-\alpha-\beta)/(1-\alpha)} \cdot H^{\beta/(1-\alpha)} \cdot \alpha^{2/(1-\alpha)} - p^P \quad (11)$$

Introduction of a public and a private R&D sector at the same time has created a wedge between society's rate of return from research and private sector's rate of return from research. Society's rate of return ($r + p^*$) exceeds the private sector's rate of return ($r + p^Z$). Public sector affects private sector's rate of return in two opposite directions. Through subsidy (s) and other activities that increase A, public sector increases private sector's rate of return. However, through conducting R&D and competing with private R&D sector, public sector decreases private sector's rate of return through p^P, which is negatively related to $r + p^Z$.

Deriving probability of an innovation per unit of time for private sector (p^Z), and plugging it into the equation for $Z_{j\kappa_j}$ we get the equilibrium value of private R&D spending for sector j that is currently at the quality rung of κ_j ($Z_{j\kappa_j}$), as

$$Z_{j\kappa_j} = q^{(\kappa_j+1)\alpha/(1-\alpha)} \cdot \left[\left(\frac{1-\alpha}{\alpha}\right) \cdot P_Y^{1/(1-\alpha)} \cdot A^{1/(1-\alpha)} \cdot L^{(1-\alpha-\beta)/(1-\alpha)} \cdot H^{\beta/(1-\alpha)} \cdot \alpha^{2/(1-\alpha)} - (r+p^P)\cdot(s\cdot\zeta)\right] \quad (12)$$

This variable denotes the amount of resources to R&D in intermediate good sector j in equilibrium. Summing up over all intermediate good sectors, overall R&D effort is

$$Z = Q \cdot q^{\alpha/(1-\alpha)} \cdot \left[\left(\frac{1-\alpha}{\alpha}\right) \cdot P_Y^{1/(1-\alpha)} \cdot A^{1/(1-\alpha)} \cdot L^{(1-\alpha-\beta)/(1-\alpha)} \cdot H^{\beta/(1-\alpha)} \cdot \alpha^{2/(1-\alpha)} - (r+p^P)\cdot(s\cdot\zeta)\right] \quad (13)$$

where $Q = \sum_{j=1}^{N} q^{\kappa_j \cdot \alpha/(1-\alpha)}$.

The variable Z is a proxy for aggregate private R&D investment for the agricultural sector. It is for institutions or firms that can claim an *exclusive* property right on their R&D product. The model shows that the level of private R&D investment is endogenously determined and depends on the decisions of economic agents and institutions that take part in the production and research process.

The first implication of the equation 13 is that when quality index (Q) increases, the level of R&D investment increases. Q is an indicator of how advanced agricultural sector is technologically. The next variable, **q** is the size of the jump in the quality index. It is taken as given in the model. Factor shares, α and (1-α) are taken as given in the model also. The next variable is price received by farmers, which is also positively related to level of R&D investment. A higher price received by farmer's increases the profit of final good producers and therefore the production of the final good. This increases the demand for intermediate goods and therefore the market size for R&D firms. The next technology variable is A(E), which is also positively related to Z. L is land input and H is labor input. These variables impact Z positively through the demand for intermediate inputs. The interest rate (r) is negatively related to the level of Z. This is due to the fact that as interest rate increases, the rate of return required from the research project that will make it feasible to undertake it will be higher. With a higher interest rate, there will be fewer projects that meet this criterion in terms of profitability, and the amount of research will be lower. The other negatively related variable is ζ, which is a form of sunk cost of research for private R&D firms. It is taken as constant in the model. Public sector activities affect private sector R&D spending through **s** and p^P in two opposite directions. Through subsidy (**0<s<1**), public sector helps private R&D firms by decreasing the cost burden for R&D firms for research projects, thus increases private R&D investment. This aid by the public sector does not need to be a monetary subsidy. Through "pre-technology research" and making its results publicly available, public sector may aid private sector in its applied technology research and decrease private sectors cost of research. However, public sector activities may lead to "crowding out" of private R&D spending as shown through the negative relation between Z and p^P (the probability of innovation by public sector). The mechanism is as follows: with public sector R&D directed at introducing a higher quality intermediate input, the public sector becomes a competitor for private R&D sector. With two sectors trying to come up with the next quality, the probability of innovation from a society's point of view increases. This increases the probability of driving an incumbent out of business compared to the case where there is only private sector. The duration of monopoly profit for private R&D firm will be lower and therefore, the expected value of innovation for a private R&D firm will be lower. This reduces the R&D effort of private firms undertaking the job and therefore private R&D spending is partly crowded out by public sector R&D spending. The net effect of public sector activities on level of private R&D spending depends on the level of parameter estimates.

6. Data

Total Factor Productivity estimates for the U.S. agricultural sector were taken from a study by Ball et al. (1997). TFP denotes the multi-factor productivity index of the ratio of aggregate crop and livestock production to aggregate production inputs. These TFP estimates were computed using a Fisher's index procedure, which is a discrete approximation to a Divisia index.

Public agricultural R&D spending data were taken from a study by Day and are provided in the USDA ERS website. Data for federal and state R&D expenditures were derived from USDA Inventory of Current Research; data for private sector R&D expenditures are from Klotz, Fuglie and Pray (1995). The series is in thousands of 1996 dollars converted from current dollars by Research Deflator[7]. Public agricultural R&D spending data include three major spending categories by source of funds. The first category is federal funds for agricultural R&D, which is provided by USDA and other institutions. The second category of public R&D spending includes state funds given to SAES and cooperating institutions. The third category includes funds given by private sector to state institutions.

Private agricultural R&D spending is estimated by Klotz, Fuglie and Pray (1995) and is provided on the USDA ERS website. The series is in thousands of 1996 dollars converted from current dollars by Research Deflator. The industries included are plant breeding, agricultural chemicals, farm machinery, veterinary pharmaceuticals (animal health), and food and kindred products. Estimates of biotechnology expenditures in private sector biotechnology firms are not included in these estimates in order to avoid double counting. The agricultural industries already included have biotechnology research expenditures within their R&D expenditures. The series is in thousands of 1996 dollars converted from current dollars by Research Deflator.

Agricultural extension spending includes total funds for cooperative extension by funding source, which are federal, state and county. The source for these data is Woods for 1960-1994 and CSREES for 1995-1996. The series is in thousands of 1996 dollars converted from current dollars by Research Deflator.

Agricultural patent data were taken from the U.S. Historical Patent Data Set provided in the website http://www.wellesley.edu/Economics/johnson. Agricultural patent data was created based on Wellesley Technology Concordance (WTC) and Yale Technology Concordance (YTC). As International Patent Classification (IPC) system distinguishes patents by type of product or process, it does not provide information on number of patents granted by industry, and therefore are of limited use for economic analysis conducted in this study[8]. YTC is designed to translate these IPC definitions of patents to Industries of Manufacture (IOM) and Sectors of Use (SOU). WTC is developed by Johnson as a

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[7]Research Deflator is from a study by Klotz, Fuglie and Pray (1995) and is used to deflate public and private R&D spending, and extension funds. Previous studies show that the cost of conducting research generally rises faster than the overall rate of inflation (Pardey, Craig and Hallaway (1989), Huffman and Evenson (1993)). Klotz et al. (1995) constructs a Research Deflator following the methodology developed in Pardey et al. (1989).

[8] For example, under USPC (a system used by the U.S.) patents are classified according to how they do a certain task, rather than by the service they provide. A heart pump is classified as a pump, not a medical device.

concordance between U.S. Patent Classification system and the internationally standard IPC. The output from WTC is used as input into YTC, and historical patent series for the U.S. is created according to IOM and SOU[9]. The patent data set used in this study is calculated based on the U.S. Historical Patent Data Set. It is the total number of patents that are used by the agricultural sector. The sectors included in the calculation of patent data are livestock, crops and combo farms, fruits and vegetables, horticulture, service to livestock, service to crops, other.

Quality index is created as a stock variable from number of agricultural patents using Perpetual Inventory Method according to the following formulae[10]:

$$Q_{t+1} = Q_t \cdot (1-\delta) + P_{t+1} \tag{14}$$

$$Q_0 = P_0\left(\frac{1+g}{g+\delta}\right) \tag{15}$$

where g is the sample average growth rate of number of patents granted in a year, P_{t+1} is the number of patents granted each year, and δ is the depreciation rate, taken as 0.05.

Ex-post real interest rate (r_t) is calculated according to the below formula:

$$r_t = n_t - \left(\frac{D_{t+1} - D_t}{D_t} * 100\right) \tag{16}$$

where n_t denotes short-term annual nominal interest rate which is chosen as the stop yield rate at auction of US Treasury Bills with 1 year maturity. D_t is the Consumer Price Index. Inflation rate is calculated as the percent change from a year ago of CPI.

Index of prices received by farmers is obtained from USDA NASS. It includes all farm products, and is deflated by the GDP deflator.

7. Empirical Analysis

7.1 Empirical Specification

The quality innovation model utilized in this study shows the link between technical change and Total Factor Productivity. The sources of technical change are identified as public and private R&D investments, and increases in human capital of farmers. The empirical work based on this model has three objectives. The first objective is to measure and explain technical change. The second objective is to test the implications of the model on the relation between technical change and productivity. The third one is to explore the factors that determine private agricultural R&D spending. Although the model is originally a macroeconomic model, it has been modified to reflect the characteristics of the U.S. agricultural sector

[9] The sectors of use are the demand sectors that use the new technology. The industries of manufacture are the supplying sectors of innovations that develop the innovations. For example, a pesticide sprayer has chemical fertilizer or agricultural machinery as its industry of manufacture, but it has field crop sector as its sector of use.

[10] Schimmelpfennig and Thirtle (1999), Esposti (2000)

and it will be applied to data on the U.S. agricultural sector.

The conceptual model for the TFP equation is based on the equation 7. There are two venues of technical change in this equation. One is through increases in Q (increases in the quality of intermediate inputs) and the second is through increases in A(E). A proxy for $Q.A(E)^{1/(1-\alpha)}$ is the TFP estimates for the U.S. agricultural sector. If the observed value is $\widetilde{TFP}_t$ and the real value is $TFP_t = Q_t \cdot A(E)_t^{1/(1-\alpha)}$, then the relationship is $\widetilde{TFP}_t = TFP_t + v_t$, with an additive error. In this equation $Q = \sum_{j=1}^{N} q^{\kappa_j \cdot \alpha/(1-\alpha)}$ is an aggregate quality index for the agricultural sector. A(E) is the level of technology not accounted by the quality index. In this definition, changes in TFP are divided into their components. Q is a stock of inventions available to producers. Technical change occurs (Q increases) due to R&D efforts of public and private sector. R&D investments lead to increases in TFP through their impact on Q.

The second component, A(E), denotes the portion of TFP that changes through any activity that connects the users of technology with the new technology. It is a proxy for any activity that increases the human capital in the agricultural sector. The factors that increase human capital of farmers are extension services carried out by the land-grant universities and education of farmers. Here, A(E) is modeled to be a function of extension services funds. This is also in line with previous empirical work that found the positive impact of extension funds[11].

How to measure and explain the Quality Index?

The aggregate quality index (Q) is a measure of the stock of inventions. In order to measure Q, agricultural patent data are used. Patents provide a good, though imperfect, approximation to inventive activity and this type of data have been used before. Schimmelpfennig and Thirtle (1999) have used patent data to calculate private and public R&D stocks in the agricultural sector. Eaton and Kortum (1996) have used patent data as an indirect measure of innovation while exploring the implications of a quality innovation model on the relation between productivity and innovation. As Q is a stock variable, a proxy for Q will be calculated from agricultural patents based on equations 14 and 15.

The patent data by industry is predicted using information on the distribution of patenting across technology fields. Caution should be exerted when using patent data to measure technical change and inventive activity. First of all, not all innovations are patented; some are kept as trade secrets and some remain unprotected in the public domain. Second, not all patents are equally important. So a count of patents may overrepresent the inventiveness of sectors which protect many small inventions and underrepresent sectors which protect less but more important inventions. Third, farmers do not adopt all patented inventions. If true quality index is shown with Q and Q* is the observed quality index, then the

[11] Huffman and Evenson (1992, 1993), Makki et al. (1999)

relationship is $Q_t^* = Q_t + e_t$ where quality index is measured with an additive error.

To explain Q, the mechanism of the model about how technical change occurs will be employed. Public and private R&D investments lead to inventions. Each invention in sector j raises $q^{\alpha\kappa_j/(1-\alpha)}$ to $q^{\alpha(\kappa_j+1)/(1-\alpha)}$, and raises Q. The conceptual model for empirical study for quality index is proposed as follows: $Q_t = f(Z_t, R_t)$ where Z_t is private agricultural R&D spending and R_t is public agricultural R&D spending.

<u>TFP and technical change:</u>

The quality innovation model establishes a direct and positive link between TFP and technical change. The empirical equation for TFP is proposed as $TFP_t = f(E_t, Q_t)$ where E_t is extension funds, and Q_t is stock of patents. E_t is added to incorporate the effect of changes in human capital on TFP_t. Q_t is added to explore the impact of inventions on TFP_t. In this specification, public and private R&D investments affect TFP_t indirectly through Q_t.

<u>What determines private R&D investment?</u>

The model also provides an analysis of private R&D investment (equation 13). When $TFP = Q \cdot A(E)^{1/(1-\alpha)}$ is plugged into this equation, we get

$$Z = q^{\alpha/(1-\alpha)} \cdot \left[\left(\frac{1-\alpha}{\alpha} \right) \cdot P_Y^{1/(1-\alpha)} \cdot L^{(1-\alpha-\beta)/(1-\alpha)} \cdot H^{\beta/(1-\alpha)} \cdot \alpha^{2/(1-\alpha)} \cdot TFP - Q \cdot (r + p^P) \cdot (s \cdot \zeta) \right] \tag{17}$$

The variable, Z, is private agricultural R&D investment. ζ, α, $(1-\alpha)$, and **q** are constant. **s** and p^P correspond respectively to the complementary and substitute effect of public R&D spending. **r** is interest rate. Land (L) and labor (H) inputs are negatively correlated with TFP in the model and also in the estimation of TFP. Thus, they are not included in the empirical specification for Z. The third empirical equation is proposed as $Z_t = f(R_t, r_t, TFP_t, P_{Yt})$ where R_t is public R&D spending and it corresponds to the variables **s** and p^P. r_t is ex-post real interest rate. TFP_t is total factor productivity, and it corresponds to the total effect of A(E) and Q. P_{Yt} is an index of price received by farmers deflated by the GDP deflator.

A system of equations with three endogenous variables is set up as follows:

$$TFP_t = f(E_t, Q_t) \tag{18}$$

(+) (+)

$$Q_t = g(Z_t, R_t) \tag{19}$$

(+) (+)

$$Z_t = h(R_t, r_t, TFP_t, P_{Yt}) \tag{20}$$

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

The data used are in logs except ex-post real interest rate[12]. Stationarity tests were conducted using the Augmented Dickey-Fuller tests. All data are found to be non-stationary. Therefore, I took the first differences of the variables in the system. As first differenced log data is approximately equal to the growth rate, this specification is also in line with the fact that the empirical work is based on a growth model. Stationarity tests were conducted on the first differenced data series, as well. All first differenced data were stationary except the quality index. As the flow of patent data by the sector of use is stationary, it is used as a proxy for the first differenced quality index, ΔQ_t.

$$\Delta Q_t = Q_t - Q_{t-1} = P_{t-1} + \varepsilon_t \tag{21}$$

The theoretical model assumes an instantaneous rate of adoption of new technology to obtain closed form solutions to the variables in the model. However, in reality creation and adoption of new technology takes time. To incorporate this observation into empirical analysis, lags of extension funds and public and private R&D investments will also be included as explanatory variables. Previous empirical research has found that the results of private and public R&D activities and extension services have an impact on TFP with lags[13]. Therefore, lagged values of public R&D spending, private R&D spending, and extension funds are included. The equations for ΔTFP_t, P_t and ΔZ_t are set up based on these concerns. The appropriate lag length was chosen by the Likelihood Ratio test.

The final system of equations is as follows:

$$\Delta TFP_t = f(\sum_{i=1}^{k} \alpha_i \cdot \Delta E_{t-i}, P_{t-1}) \tag{22}$$

$$P_t = g(\sum_{i=1}^{l} \alpha_i \cdot \Delta Z_{t-i}, \sum_{i=1}^{m} \alpha_i \cdot \Delta R_{t-i}) \tag{23}$$

$$\Delta Z_t = h(\sum_{i=1}^{n} \alpha_i \cdot \Delta R_{t-i}, \Delta r_t, \sum_{i=1}^{v} \alpha_i \cdot \Delta TFP_{t-i}, \Delta P_{Yt}) \tag{24}$$

The three endogenous variables in the system of equations are ΔTFP_t, P_t and ΔZ_t. The exogenous variables are extension funds (ΔE_{t-i}), price received by farmers (ΔP_{Yt}), ex-post real interest rate (Δr_t), public R&D spending (ΔR_{t-i}), and lagged private R&D spending (ΔZ_{t-i}). In this simultaneous equations model, the endogenous variables appear as explanatory variables in the right hand side of equations. Therefore, explanatory variables are not distributed independently of the disturbance terms. Also, an estimator that has the properties of Generalized Least Squares estimator is needed to remove the inefficiency of parameter estimates by using the cross-equation correlations of disturbances. One estimator that has both of these properties is Three-Stage Least Squares estimator. Therefore, it will be adopted as the estimation technique for the simultaneous system of equations.

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[12] $\log(1+r) = r$ for small values of r

[13] Huffman and Evenson (1992,1993), Makki et al. (1999)

7.2 Empirical Results

The three equations in the system were first estimated separately with ordinary least squares and different lag lengths for the explanatory variables in order to choose the optimum lag length. Likelihood ratio tests indicated that the optimum lag length for the TFP equation is five lags for extension, and zero lags for patent. The final model for TFP is: $\Delta TFP_t = f(\sum_{i=1}^{6} \alpha_i \cdot \Delta E_{t-i}, P_{t-1})$.

For the patent equation, Likelihood Ratio tests showed that ten lags for public and private R&D spending are optimal. The final model for agricultural patents is: $P_t = g(\sum_{i=1}^{11} \alpha_i \cdot \Delta R_{t-i}, \sum_{i=1}^{11} \alpha_i \cdot \Delta Z_{t-i})$.

For the private R&D spending equation Likelihood ratio tests revealed that the model with one lag length for public R&D spending should be chosen. The appropriate lag length for TFP was zero, although the test result for two lags was very close. Two models for private R&D spending are chosen:

$\Delta Z_t = h(\sum_{i=1}^{2} \alpha_i \cdot \Delta R_{t-i}, \Delta r_t, \Delta TFP_t, \Delta P_{Yt})$ and $\Delta Z_t = h(\sum_{i=1}^{2} \alpha_i \cdot \Delta R_{t-i}, \Delta r_t, \sum_{i=1}^{3} \alpha_i \cdot \Delta TFP_{t-i}, \Delta P_{Yt})$

The results are presented in Tables 1 and 2. In Table 1, the first equation has ΔTFP_t as the dependent variable. This equation is set up to explore the link between technical change and TFP growth. The sum of the coefficients of all extension variables is positive and Likelihood Ratio test shows that extension variables are jointly significant. Agricultural patent variable has a positive coefficient estimate, although it is not significant.

The agricultural patent equation is basically a production function for patents where inputs are private and public R&D spending. The estimation results show that the sum of public R&D spending variables is positive and Likelihood Ratio test shows that these variables are jointly significant. Sum of private R&D spending variables is positive and Likelihood Ratio test reveals that these variables are jointly significant as well. These findings are in line with the prediction of the theoretical model. Both public and private R&D spending perform well as explanatory variables in a patent production function.

The estimates for the private R&D spending equation indicate that public R&D spending has a positive impact on the private R&D spending, although public R&D spending variables are not jointly significant. The theoretical model predicted that public R&D spending may affect private R&D spending in two opposite directions. Through subsidies, public R&D sector complements private R&D sector and contributes to private R&D activities. However, public sector activities may lead to “crowding out” of private R&D spending through conducting R&D and competing with the private R&D sector. These empirical results suggest that the complementary effect of public R&D spending exceeds its “crowding out” effect on private R&D spending, and that existence of a strong public R&D sector is beneficial for the private R&D sector. Ex-post real interest rate has a negative effect on the private R&D spending, which is in line with the model's prediction. TFP has a positive and insignificant coefficient estimate. The model showed that the higher the TFP, the higher the private R&D spending. This finding shows that higher productivity growth rate in the agricultural sector has a positive impact on the growth rate of private R&D spending. Price received by farmers has a positive and insignificant coefficient, as well.

Table 2 shows the estimation results with lagged TFP variables added to the private R&D spending equation. This produces some minor changes in the estimation results. The sum of TFP variables is now negative and close to zero, although jointly insignificant. This is in contrast to what the model predicted in terms of the impact of TFP growth on private R&D spending growth. The system weighted R^2 decreases slightly from 0.7172 to 0.6601.

The above findings indicate the implications of the theoretical model are supported by the U.S. agricultural sector data. I find strong positive impacts of extension funds on TFP growth rate. Agricultural patents are a proxy for the inventions available to farmers and I find that more patents lead to higher TFP growth. I also find that public and private R&D spending have positive and significant effects on the flow of agricultural patents. Although public R&D institutions seek patent rights for their inventions less aggressively compared to private institutions, the contributions of the public sector research results are found to be as effective as the contribution of private sector to creation of new technology. One reason for this finding can be the fact that public sector makes its research results available to general public, and therefore contributes to the creation of new technology. Public R&D spending is found to lead to higher private R&D spending. This finding combined with the above result supports the idea that continuing of public R&D sector activities are not only necessary for technical progress, but also benefits the private R&D sector.

8. Concluding Remarks:

The study presented here has utilized an endogenous growth model to analyze technical change in the U.S. agricultural sector. In the theoretical part of the study, a quality innovation model was used in which technical change is the result of research and development activities carried out by the public and the private R&D sector. The link between total factor productivity and technical change was explored in the model and the TFP growth was separated into an invention component and other components. This way, the relationship between inventions and productivity was distinguished from the more general relationship between the R&D sector and overall productivity growth. 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 was included through a subsidy that decreases the cost of private R&D firms. Public R&D sector was also a substitute to private R&D sector as it engages in activities that attempt to create higher quality intermediate goods. In the theoretical model, the net effect of public R&D spending on private R&D spending was ambiguous.

In the empirical analysis, agricultural patent data were used to calculate a proxy for technical change, and then the relation between TFP and agricultural patents was explored. Extension service funds were used as a proxy for human capital of farmers and are included in the TFP equation as well. Second, a patent production function was estimated with inputs as public and private agricultural R&D spending. Third, the determinants of private agricultural R&D spending were explored. One important feature of the model was that private R&D spending was endogenously determined. In the empirical specification, TFP was an explanatory variable for the private R&D spending as well as being a dependent variable in the system of equations. That is one difference from the previous empirical literature that explored the impacts of R&D investments on TFP and took private R&D spending as exogenous. In this study a simultaneous system of equations was set up with dependent variables as TFP, agricultural patents, and private agricultural R&D spending. The model was estimated with time series data from U.S. with three stage least squares, 1960-1996.

The empirical analysis employed total number of granted patents that are used by the agricultural sector. As food and kindred products R&D produces inventions that are greatly used by the agricultural sector, the private R&D spending data included not only agricultural inputs R&D, but also food and kindred products R&D. The empirical results were fairly consistent with the prior expectations based on the theory. A positive relationship between TFP growth in the agricultural sector and agricultural patents was found. Current and past public and private R&D investments in agricultural sector were found to have a significant and positive effect on agricultural patents. It was found that public R&D investments do not crowd out private R&D investments and that existence of an effective public R&D sector was advantageous for the private R&D sector. This result combined with the finding that public R&D spending contributes to agricultural patents gives support to the idea that continuing of public R&D sector activities are important for technical progress in the U.S. agricultural sector.

These results provide some guidance about the feasibility of R&D based growth models and their applicability to the U.S. agricultural sector. The creation of new technology through R&D is central to the recent endogenous growth models and therefore these models provide a fruitful framework through which technical change in U.S. agricultural sector can be analyzed.

TABLE 1. REGRESSION RESULTS[a]

Variable	Dependent Variable: TFP	Patents	Private R&D Spending
Intercept	-0.155	8.166**	0.013
	(0.693)	(0.255)	(0.026)
Extension Funds[b]	0.263*		
Patents	0.020		
	(0.079)		
Public R&D Spending[b]		17.985*	0.388
Private R&D Spending[b]		5.821*	
Real Interest Rate			-0.104
			(0.656)
TFP			0.415
			(0.841)
Price received			0.184
			(0.478)
N	26	26	26

a. These are three-stage least squares estimates. Standard errors are in parentheses. ** and * denote significance at the 0.05 level and 0.10 level respectively. System weighted $R^2 = 0.7172$. Instruments are lagged TFP, lagged Patent, lagged private R&D, lagged land input.

b. LR test for Extension funds is $17.27 > \chi^2(6) = 10.64$ in ΔTFP equation, LR test for Public R&D is $58.04 > \chi^2(11) = 17.28$ in Patent equation, LR test for Private R&D is $67.24 > \chi^2(11) = 17.28$ in Patent equation, LR test for Public R&D is $1.21 < \chi^2(2) = 4.61$ in ΔPrivate R&D equation.

TABLE 2. REGRESSION RESULTS[a]

	Dependent Variable		
Variable	TFP	Patents	Private R&D Spending
Intercept	-0.876	8.191**	0.029
	(1.482)	(0.306)	(0.067)
Extension Funds[b]	0.201*		
Patents	0.102		
	(0.169)		
Public R&D Spending[b]		17.181*	0.129
Private R&D Spending[b]		5.809*	
Real Interest Rate			-0.687
			(1.183)
TFP[b] (2 lags)			-0.051
Price received			0.299
			(0.483)
N	26	26	26

a. These are three-stage least squares estimates. Standard errors are in parentheses. ** and * denote significance at the 0.05 level and 0.10 level respectively. System weighted $R^2 = 0.6601$. Instruments are lagged TFP, lagged Patent, lagged private R&D, lagged land input.

b. LR test for Extension Funds is $19.45 > \chi^2(6) = 10.64$ in ΔTFP equation, LR test for Public R&D is $44.37 > \chi^2(11) = 17.28$ in Patent equation, LR test for Private R&D is $46.36 > \chi^2(11) = 17.28$ in Patent equation, LR test for Public R&D is $0.14 < \chi^2(2) = 4.61$ in ΔPrivate R&D equation, LR test for TFP is $2.08 < \chi^2(3) = 6.25$ in ΔPrivate R&D equation.

REFERENCES:

Agricultural Outlook (1999) 'Biotechnology Research: Weighing the Options for a New Public-Private Balance' USDA ERS

Agricultural Resources and Environmental Indicators 1996-1997 USDA, ERS, Natural Resources and Environment Division, Agricultural Handbook No. 712, Chapter 5, pp. 241-254

Aghion, P. and P. Howitt (1992) 'A Model of Growth through Creative Destruction' Econometrica, vol. 60, no. 2, pp. 323-351

Ahearn, A., J.Yee, E.Ball and R.Nehring (1998) 'Agricultural Productivity in the United States' USDA, ERS, Resource Economics Division, Agriculture Information Bulletin, no.740

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., M.C. Marra, P.G. Pardey and T. Wyatt (2000) 'Research Returns Redux: A Meta-Analysis of the Returns to Agricultural R&D' The Australian Journal of Agricultural and Resource Economics, vol. 44(2), pp.185-215

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. and R. Venner (2000) 'The Effects of the U.S. Plant Variety Protection Act on Wheat Genetic Improvement' EPTD Discussion Paper No. 62, Washington D.C. IFPRI

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

Berman, E., (2000) 'Does Factor Biased Technical Change Stifle International Convergence? Evidence from Manufacturing' Working Paper #7964, NBER, October

Blanchard, O. (1997) 'The Medium Run' Brookings Papers on Economic Activity 2, pp. 89-158

Blanchard, O. (1998) 'Revisiting European Unemployment: Unemployment, Capital Accumulation, and Factor Prices', typescript, MIT, May

Butler, L.J. and B.W. Marion (1985) 'The Impacts of Patent Protection on the U.S. Seed Industry and Public Plant Breeding' North Central Regional Research Publication 304, North Central Project 117, Monograph 19. Madison WI: Research Division, College of Agricultural and Life Sciences, University of Wisconsin

Caswell, M.F., K.O. Fuglie, and C.A. Klotz-Ingram (1994) 'Agricultural Biotechnology: An Economic Perspective' USDA, Economic Research Service, AER-687

Chavas J.P and T.L. Cox (1992) 'A Nonparametric Analysis of the Influence of Research on Agricultural Productivity', American Journal of Agricultural Economics, vol. 74(3), pp.583-91

Day, K., P. W. Heisey, C. Klotz-Ingram and G.B. Frisvold (2000) 'Competitive Grants and the Funding of Agricultural Research in U.S.' Paper presented at AAEA meetings

Dixit, A.K. and J.E. Stiglitz (1977) 'Monopolistic Competition and Optimum Product Diversity' American Economic Review, vol. 67, no. 3, pp. 297-308

Esposti, R. (2000) 'Stochastic Technical Change and Procyclical TFP: The Case of Italian Agriculture' Journal of Productivity Analysis, vol. 14, pp. 119-141

Eaton J. and S. Kortum (1996) 'Trade in Ideas: Patenting and Productivity in the OECD' Journal of International Economics, vol. 40, pp. 251-78

Ethier, W.F. (1982) 'National and International Returns to Scale in the Modern Theory of International Trade' American Economic Review, vol. 72, no.3, pp. 389-405

Evenson, R.E. and C.E. Pray (1991) 'Research and Productivity in the Asian Agriculture' Cornell University Press, Ithaca and London

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

Good, D.H., M.I. Nadiri and R.C. Sickles (1996) 'Index Number and Factor Demand Approaches to the Estimation of Productivity' NBER Working Paper No. W5790

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, no. 3, pp. 762-766

Griliches, Z. (1996) 'The Discovery of the Residual: A Historical Note' Journal of Economic Literature, vol.34, issue 3, pp.1324-1330

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

Heisey, P.W., C.S. Srinivasan and C. Thirtle (2001) 'Public Sector Plant Breeding in a Privatizing World', USDA ERS, Agriculture Information Bulletin, No. 772

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, No.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

Johnson, S.R. and S.A. Martin (1993) 'Industrial Policy for Agriculture in the Global Economy' Iowa State University Press, AMES

Jorgenson, D.W. and F. Gollop (1992) 'Productivity Growth in U.S. Agriculture: A Postwar Perspective' American Journal of Agricultural Economics, vol.74, no.3, pp. 745-750

Jorgenson, D.W. and Z. Griliches (1995) 'The Explanation of Productivity Change' in 'Productivity Volume 1: Postwar U.S. Economic Growth' ed. by D. W. Jorgenson, Chapter 3, MIT Press, Cambridge, MA

Kahn, J.A and J.S. Lim (1998) 'Skilled Labor-Augmented Technical Progress in U.S. Manufacturing' Quarterly Journal of Economics, vol. 108, pp. 1281-1305

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

Kortum, S. and J. Putnam (1997) 'Assigning Patents to Industries: Tests of the Yale Technology Concordance' Economic Systems Research, vol. 9, pp. 161-175

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, no.2, pp. 371-388

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

Pardey, P., B.J. Craig and M.L. Hallaway (1989) 'U.S. Agricultural Research Deflators: 1890-1985' Research Policy, vol. 18, pp. 289-96

Pray, C. and C. Neumeyer (1989) 'Trends and Composition of Private Food and Agricultural R&D Expenditure in the U.S.' Dept. of Agricultural Economics, Rutgers University, NJ

Romer, P. (1987) 'Growth Based on Increasing Returns due to Specialization' American Economic Review, vol. 77, no. 2, pp. 56-62

Romer, P. (1990) 'Endogenous Technological Change' Journal of Political Economy, vol. 98, No.5, part 2, pp. S71-102

Schimmelpfennig, D., and C. Thirtle (1994) 'Cointegration and Causality: Exploring the Relationship between Agricultural R&D and Productivity' Journal of Agricultural Economics, vol. 45, pp. 220-31

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, vol. 17(4), pp. 457-468

Seater, J. (2001) 'Technical Change and Factor Shares' NCSU Working Paper

Shane, M., T. Roe, and M. Gopinath (1998) 'U.S. Agricultural Growth and Productivity: An Economywide Perspective' USDA ERS, Agricultural Economic Report No. 758

Spence, M. (1976) 'Product Selection, Fixed Costs, and Monopolistic Competition' Review of Economic Studies, vol. 43, no. 2, pp. 217-235

Stiroh, K. (2000) 'What Drives Productivity Growth?' Federal Reserve Bank of New York, July