ABSTRACT

TOKGOZ, SIMLA. Technological Change in the U.S. Agriculture: The Role of Public and Private R&D. (Under the Direction of Michele C. Marra and Mitch Renkow)

The objective of the study is to explore the relationship between TFP growth in the U.S. agricultural sector and R&D investments. To this end, an endogenous growth model is utilized to understand the link between TFP growth and technological change, and to examine how R&D investments lead to technical change. The main feature of the model is that R&D investments and technical change are endogenously determined in the economic system. The model in this study contributes to the existing literature on endogenous growth theory by incorporating a role for the public R&D sector. The public R&D sector helps the private R&D sector through subsidies; however it also may crowd out part of private R&D sector investment by competing with it when trying to create new and better technology. In the empirical analysis, first the link between TFP growth and technical change is explored using agricultural patent data as a proxy for technical change. Next, a patent production function is estimated with explanatory variables as public and private R&D investments. Then, the factors that determine private agricultural R&D investment are examined. To pursue these objectives, a system of equations is estimated with time series data for U.S. with seemingly unrelated regression technique. A negative relationship between TFP growth in the agricultural sector and agricultural patents is found, though the coefficient estimate is insignificant. Public R&D and extension services have a positive and significant impact on TFP. Public and private agricultural R&D investments have a positive effect on agricultural patents. It is also found that public R&D investment does not crowd out private R&D investment.

TECHNOLOGICAL CHANGE IN THE U.S. AGRICULTURE:

THE ROLE OF PUBLIC AND PRIVATE R&D

by

SİMLA TOKGÖZ

A dissertation submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

ECONOMICS

Raleigh

2002

APPROVED BY:

_____ _____

_____ _____

Co-chair of Advisory Committee - Co-chair of Advisory Committee

To my family, without whose encouragement I could not have started this journey

and to my friends, without whose support I could not have finished it

BIOGRAPHY

Simla Tokgöz was born in Ankara, Turkey in 1974 and attended T.E.D Ankara Koleji, from which she graduated in 1991. She attended Middle East Technical University (Orta Doğu Teknik Üniversitesi) and studied Economics. She graduated in 1995 from O.D.T.Ü and enrolled in the Master's program of the same department. She became a teaching assistant at O.D.T.Ü. in 1995 and decided to pursue an academic career in Economics. To this end, she entered the Graduate School at North Carolina State University to study Economics. She accepted an Assistant Scientist position at Center for Agricultural and Rural Development Institute at Iowa State University.

ACKNOWLEDGEMENTS

I would like to thank, first of all, Dr. Mitch Renkow and Dr. Dan Hallstrom for their incredible support during the process of writing this dissertation. During my search for a dissertation topic, they have not only provided insightful and invaluable comments, but also were patient enough to listen to me any time I needed it during my rather frustrating search. It has been a very pleasing experience to work with them and I have learned a great deal about conducting research during our endless discussions about every single aspect of my dissertation.

I would like to express my deep gratitude to Dr. Michele Marra, as well, for her guidance and encouragement throughout the various stages of this dissertation. Dr. David Dickey provided valuable help and insights on different aspects of this dissertation.

I am also very grateful to Dr. Thomas Grennes and Dr. John Seater for their support and guidance during my Ph.D. journey at North Carolina State University. Last, but not least, I would like to thank Dr. Jim Easley, our Graduate Director, for his kindness and optimism when I needed it most.

TABLE OF CONTENTS

INDEX OF TABLES

INDEX OF FIGURES

Chapter 1

INTRODUCTION

The performance of 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.[1] 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 total factor productivity (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 research and development (R&D) and extension services.

Agriculture in the U.S has a history of public sector research & development that dates back to the second half of the 19th 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 typically cited as the main elements contributing to the increasing

role of private R&D in agriculture.

This study 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 technical change in the agricultural sector is examined, using agricultural patent data as a proxy for technical change. An analysis of the determinants of private agricultural R&D investment is conducted, as well. 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

[1] Table 1.1

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. over the period 1960-1996 with seemingly unrelated regression technique. The dependent variables are TFP, agricultural patents, and private agricultural R&D investment.

The empirical results are fairly consistent with the predictions of the theoretical model. The main finding is that public R&D activities and extension services have a positive impact on TFP growth. There is a negative relationship between TFP growth in the agricultural sector and agricultural patents, though this coefficient estimate is insignificant. Past public and private R&D investments in agricultural sector have a positive effect on agricultural patents. It is found that public R&D investment does not crowd out private R&D investment. TFP has a negative impact on private R&D investment, but all the coefficient estimates are insignificant.

In the final step of the empirical analysis, marginal internal rates of return to public and private R&D investments are calculated. Because of the non-significance of the patents variable in the TFP equation, these computations are based on reduced form estimates of the elasticity of TFP with respect to public and private research. The rate of return to public R&D is -7 percent, and the rate of return to private R&D is between 50-1696 percent. The rate of return to extension services ranges between 105-128 %.

1.1 The 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.[2] USDA and land grant systems were established in 1862, whereas SAES's were established in 1887. In 1914, with the passage of the Smith-Lever Act and subsequent development of the Cooperative Extension Service, a separate system was set up for extension services. 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 of 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 (pre-technology research) and the private sector concentrating on applied research and technology development (Agricultural Outlook (1999), Huffman and Evenson (1993a)).[3]

[2] Land-grant universities include 1890 schools, forestry schools, and veterinary schools.
[3] Huffman and Evenson (1993a) classify R&D activities into three groups: (1) general sciences (chemistry, genetics, biology, zoology), (2)pre-technology sciences (soil physics and chemistry, plant and animal

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 (Table 1.2, Table 1.3). 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 expenditure nearly tripled in real terms, whereas public R&D spending only doubled. While public R&D spending made 53 percent of total R&D spending in 1960, this ratio dropped to 44 percent 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 the 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. In 1970, formula funds were 61 percent of federal funds going to state institutions. In 1994, this ratio fell to 30 percent (Fuglie et al. (1996)). State funds given to SAES and cooperating institutions also stagnated after 1980s and started decreasing after 1990s. The decline in the relative contribution of state governments is partly a result of the 1990-91 economic recession (Fuglie et al. (1996)). On the other hand, non-government funds

---

genetics, plant and animal pathology, plant and animal physiology), (3) technology invention (agricultural

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 percent and 21 percent in 1973 to 15 percent and 24 percent 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 percent and 12 percent in 1973 to 30 percent and 10 percent in 1992. Other areas of research also show some minor changes (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 total 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 (Table 1.4). 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

---

chemistry, plant and animal breeding, horticulture, agronomy).

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 (Agricultural Outlook (1999), Fuglie et al. (1996)).

Patent protection has been available for agricultural R&D products for a long time. "Between 1787 and 1842, a number of legislative acts were passed that refined and strengthened the U.S. intellectual property rights. These were important to the early development of the U.S. farm machinery industry" (Huffman and Evenson (1993b). 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. A PVPC gives a plant breeder proprietary ownership of a new variety for 17 years. The 1995 Supreme Court decision to restrict a farmer's right to resell protected seeds has transformed these protection certificates into utility patents.[4] 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, the 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 (Table 1.5), the evidence regarding the impact on different sectors has been mixed.

[4] When a utility patent is granted, no one may make, use, or sell the invention without the permission of the owner. It is a stronger protection than PVPC's and plant patents. It is the most important property right for biotechnology research.

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. Hybrid seeds offer a natural form of protection for intellectual property since the yield of the second-generation progeny of a hybrid declines distinctly. Thus, farmers need to buy new hybrid seed each season (Fuglie et al. (1996)).

The 1970 PVPA gave protection for new varieties of sexually reproduced seed crops other than hybrids. With this 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 has not increased.

In recent years, several scientific breakthroughs have contributed to private R&D sector activities. Tissue cell culture has reduced time required for developing new varieties. Gene transfer technologies have enabled researchers to tailor crops for specific uses such as crops that are resistant to disease, pests, or harsh environmental conditions. Advances in biotechnology such as fast and accurate DNA fingerprinting to identify patented DNA sequences have strengthened companies' ability to protect their property rights. Emergence of "enabling technologies" such as promoter genes, marker genes, specific cellular enzyme activation processes also have helped production of a biotech end product. Biotechnology protocols for creating transgenic plants have emerged that have made it easier to protect intellectual property in plant innovations. Topics related to

basic science are now included as new research agendas of large private firms such as Novartis, Monsanto, DuPont and Celera. These firms have been among the leading firms that introduced genetically modified seeds.

Intellectual property protection is also available to public sector discoveries. The 1980 Bayh-Dole Patent Policy Act permits 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 (CRADA) have been set up as a mechanism through which public and private institutions could 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 has 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. In the post-harvest technology field of international patent classification (IPC), the ratio of patents granted to public institutions is 1.3 percent for the 1963-70 period and 2.5 percent for the 1971-80 period. For six production technology fields, one modern biotechnology field and an aggregate post-harvest technology field, the ratio of patents granted to public institutions is 10 percent for 1975-80 period and 10 percent for 1980-84 period. PVPC's administered by USDA give a relatively weaker protection compared to patents. For the period of 1971-1990, USDA-SAES obtained only 11 percent of PVPC's (Huffman and Evenson (1993a)).

All these developments in the scope 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 the 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 the private sector is gaining more responsibility. For such R&D activities, public sector activities may “crowd out” private sector investment.

However, there are other areas where the role of public sector may still be needed. One such role that has been identified is provision of 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" research conducted by the public sector role. Huffman and Evenson also assert that private sector R&D can not adequately accommodate the geo-climatic specificity of agricultural technology. As the potential size of a market for a new product depends on its adaptability to geo-climatic conditions, private firms will develop and sell technologies that can be used in large areas only. Therefore, 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, extension activities, environmental and food safety regulations (Heisey et al. (2001), Agricultural Outlook (1996), Fuglie et al. (1996)).

1.2 Plan of Dissertation

The model employed in this study can be used to evaluate the relation between public and private R&D sectors. In this model, private firms conduct R&D to create intermediate goods of higher quality that are used in the production of final good. The motivation of private sector research is the compensation of successful innovators. Property rights over the production and sale of R&D products are assumed, as they are necessary to secure the reward from innovation. Recent institutional developments in the U.S. provide 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. Public sector R&D activities and private sector R&D activities are both complements to and substitutes for each other in the model. The net effect of the public sector activities on private sector is ambiguous in the theoretical model as it depends on the value of the parameter estimates.

The dissertation is organized as follows. Chapter 2 reviews relevant previous research on the analysis of impacts of research and development, and discusses the definition and measurement of technical change in neoclassical growth models. Chapter

3 describes in detail the quality innovation model and the testable implications of the model. Chapter 4 provides the empirical specification based on the theoretical model, and discusses the data used in the study. In Chapter 5, the econometric results and the calculated rates of return to research are presented. Chapter 6 summarizes the findings and concludes.

Table 1 1. Indexes of Farm Output, Input Use and Productivity, 1960-1996 (1960=100)

	Total Farm Output	*Total Farm Input*	*Total Factor Productivity*
Compound annual average growth rate			
1960-1970	1.53%	-0.47%	1.99%
1970-1980	2.09%	0.95%	1.21%
1980-1990	1.46%	-1.38%	2.89%
1990-1996	2.65%	0.05%	2.85%

Table 1. 2. Research and Development Expenditures for U.S. Agricultural Sector

Decades	*Public Sector Spending*	*Private Sector Spending*
1960-1970	3,900,596	3,465,834
1970-1980	9,577,174	8,920,673
1980-1990	21,458,524	23,467,027
1990-1996	20,691,132	24,217,767

- Thousands of Current Dollars

Table 1. 3 Research and Development Expenditures for U.S. Agricultural Sector

	Public Sector Spending	*Private Sector Spending*
Compound annual average growth rate		
1960-1970	8 %	9 %
1970-1980	11 %	12 %
1980-1990	7 %	9 %
1990-1996	4 %	5 %

- Thousands of Current Dollars

Table 1. 4. Research Expenditures by Agricultural Industries (1960-1996)

Research Program Area	*Expenditure (% of Total) 1960*	*Expenditure (% of Total) 1996*
	Million $	Million $
Plant Breeding	5.60 (2.72%)	526.13 (13.28%)
Agricultural Chemicals	27.00 (13.13%)	1,458.66 (36.83%)
Farm Machinery	75.00 (36.48%)	505.66 (12.77%)
Veterinary Pharmaceuticals	6.00 (2.92%)	323.70 (8.17%)
Food & Kindred Products	92.00 (44.75%)	1,146.64 (28.95%)
Total	205.60	3,960.79

Table 1. 5. Intellectual Property Rights Issued for New Plant Varieties (1970-1998)

	Plant Patents	*PVPC's*	**Utility Patents**
1970-1979	1530	649	9
1980-1989	2587	1538	96
1990-1998	3644	1684	1144

Chapter 2

PREVIOUS RESEARCH

2.1 Analysis of the Impacts of Research and Development

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 examined, 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.[5]

However, the mechanism by which the R&D sector causes a change in the productivity level has not been systematically explored. Research and development activities in the agriculture sector produce very diversified outcomes such as higher yielding crop varieties, better livestock breeding practices, more effective fertilizers and pesticides, better farm management skills, and new farm machinery. All of these developments help farmers to be more productive. However, when analyzing the impacts of these technical advances on the productivity level, previous studies combine all these

[5] A thorough discussion of these different methods can be found in Alston, Norton and Pardey (1995).

new products, new processes or newly acquired skills into an increase in the knowledge stock that increases the productivity level. Although, R&D sector is critical to the process of technical progress, the economics determining R&D investment is not analyzed theoretically. Furthermore, when estimating the impact of R&D on TFP, R&D spending is considered to be exogenously determined.

There have been 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 both 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".

2.2 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.

In the neoclassical model, TFP is used as a measure of technical under the assumptions of competitive factor markets and Hicks neutral technology. The aggregate production function is given by

$$Y = A \cdot X_L^{\alpha} \cdot X_K^{1-\alpha} \tag{2.1}$$

where Y is output, X_L is labor input and X_K is capital input. TFP is defined as

$$TFP = \frac{Y}{X_L^{\alpha} \cdot X_K^{1-\alpha}} = A \tag{2.2}$$

The growth rate of TFP is

$$\dot{TFP} = \dot{Y} - \left[\alpha \cdot \dot{X}_L + (1-\alpha) \cdot \dot{X}_K\right] \tag{2.3}$$

$\dot{TFP}$ 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.[6]

Jorgenson and Griliches (1995) attempt to develop better measures of inputs and outputs to improve the precision 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 equation 2.3, accurate measurement of output and input growth will lead to a more accurate 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 percent of the rate of growth of output, whereas after the corrections it explains 96.7 percent 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 size of the "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

[6] For a discussion of different measures of TFP, see Good, Nadiri and Sickles (1996).

change occurs need to be employed.

Chapter 3

QUALITY INNOVATION MODEL

The quality innovation model used in this study is 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).

3.1 Model Layout

The quality innovation model characterizes technological progress in the form of a 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.[7] 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

[7] 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

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 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. Therefore, in equilibrium only the highest quality intermediate goods are produced by R&D sector and used by final good producers to generate output.[8]

Both the public sector and private sector conduct research aimed at improving the quality of intermediate goods, and both 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. Therefore, the success of an innovator, whether public or private sector, terminates the profit flow to the previous 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

---

variety innovation model.

[8] In other words, instantaneous adoption of new technology is assumed.

of R&D investment.

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

$$Y = A(E) \cdot L^{1-\alpha-\beta} \cdot H^{\beta} \cdot \sum_{j=1}^{N} \left(\tilde{X}_j\right)^{\alpha} \tag{3.1}$$

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 $j \neq l$. So, one additional dollar of a capital good has no effect on the marginal productivity of another capital good.[9]

A(E) is the other component of technology available to final good producers. It is modeled as a function of activities that increase the human capital in the sector. These activities include extension services that help farmers adopt new technology, as well as the activities of land grant universities that increase the human capital in the sector through education of farmers.

The potential quality grades of each intermediate good are arrayed along a quality

---

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

ladder with rungs spread proportionately at an interval of q[10] (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 $\tilde{X}_j = \sum_{k=0}^{\kappa_j} q^k \cdot X_{jk}$, where 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

$$Y = A(E) \cdot L^{1-\alpha-\beta} \cdot H^{\beta} \cdot \sum_{j=1}^{N} (q^{\kappa_j} \cdot X_{ij\kappa_j})^{\alpha} \qquad (3.2)$$

In this model, it is assumed that factor shares (α, β, $(1-\alpha-\beta)$) are unchanged by technical progress. Although it is possible that these factor shares are changing over time, this is not the scope of this study.[11]

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 $(\kappa_j+1)^{th}$ quality 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 $(\kappa_j+1)^{th}$ innovation

---

Thus $X_{j\kappa_j}$ can not be determined separately from other intermediate goods. With this 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.

[10] See Eaton and Kortum (1996) for a model where the step size of the invention, q, is stochastic.

[11] For studies that focus on factor-biased technical change, see Kahn and Lim (1998), Blanchard (1997,1998), Berman (2000), Seater (2001).

occurs). This duration is random as it depends on the uncertain outcomes of research efforts by both R&D sectors.

3.2 Profit Maximization

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

$$\max_{L,H,X_{j\kappa_j}} \pi^{FG} = P_{AGR} \cdot Y - i \cdot L - w \cdot H - \sum_{j=1}^{N} P_{j\kappa_j} \cdot X_{j\kappa_j} \tag{3.3}$$

where P_{AGR} 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 private researcher, who creates a higher quality good in sector j, gains the monopoly right to produce and sell that intermediate good at that quality level. The marginal cost production of intermediate good is 1 for all qualities. The monopolist producer of the intermediate 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

$$\max_{P_{j\kappa_j}} \pi^{RD} = (P_{j\kappa_j} - 1) \cdot X_{j\kappa_j} \tag{3.4}$$

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 the MC.

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

$$X_{j\kappa_j} = P_{AGR}^{1/(1-\alpha)} \cdot A(E)^{1/(1-\alpha)} \cdot L^{(1-\alpha-\beta)/(1-\alpha)} \cdot H^{\beta/(1-\alpha)} \cdot \alpha^{2/(1-\alpha)} \cdot q^{\kappa_j \cdot \alpha/(1-\alpha)} \qquad (3.5)$$

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. Therefore, 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: $(1/\alpha),(1/\alpha \cdot q),(1/\alpha \cdot q^2)...$ The marginal cost of production for each intermediate good is 1. If $(1/\alpha \cdot q) < 1$, 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. If $\alpha \cdot q < 1$, then the limit pricing strategy employed in Grossman and Helpman (1991) could be followed with the same result. Either way, the price of intermediate good is a mark-up over the marginal cost of production. Only the best available quality of each intermediate good is produced and used.[12]

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

3.3 Implications for Equilibrium R&D Effort

The equilibrium level of agricultural output is derived as

$$Y = \sum_{j=1}^{N} q^{\kappa_j \cdot \alpha/(1-\alpha)} \cdot A(E)^{1/(1-\alpha)} \cdot P_{AGR}^{\alpha/(1-\alpha)} \cdot L^{(1-\alpha-\beta)/(1-\alpha)} \cdot H^{\beta/(1-\alpha)} \cdot \alpha^{2\alpha/(1-\alpha)} \quad (3.6)$$

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

$$Y = Q \cdot A(E)^{1/(1-\alpha)} \cdot P_{AGR}^{\alpha/(1-\alpha)} \cdot L^{(1-\alpha-\beta)/(1-\alpha)} \cdot H^{\beta/(1-\alpha)} \cdot \alpha^{2\alpha/(1-\alpha)} \quad (3.7)$$

Technical change in equation 3.7 is attained through increases in $Q \cdot A(E)^{1/(1-\alpha)}$. It is divided into two parts: Q and $A(E)^{1/(1-\alpha)}$. The first part, quality index, increases with respect to R&D efforts of public and private R&D firms trying to come up with the next higher quality intermediate good.

To analyze the determinants of changes in this quality index, 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 incentive to innovate for private firms comes from the flow of monopoly profit. The κ_j^{th} innovator 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.

Each R&D success is random, and 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 $p^Z_{j\kappa_j}$. The 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.[13]

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

$$p^Z_{j\kappa_j} = Z_{j\kappa_j} \cdot \phi(\kappa_j) \tag{3.8}$$

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 3.8, 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 in 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 $p^Z_{j\kappa_j} \cdot E(V_{j,\kappa_j+1})$. This value is derived using the probability of innovation by a private R&D firm. The expected flow of 'net' profit from research in a sector that is currently at quality rung κ_j is

---

is why public sector may crowd out private sector.

3.4 Private and Social Rates of Return

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

$$r + p^* = \phi(\kappa_j) \cdot q^{(\kappa_j+1)\cdot\alpha/(1-\alpha)} \cdot \left(1-\alpha/\alpha\right) \cdot P_{AGR}^{1/(1-\alpha)} \cdot A(E)^{1/(1-\alpha)} \cdot L^{(1-\alpha-\beta)/(1-\alpha)} \cdot H^{\beta/(1-\alpha)} \cdot \alpha^{2/(1-\alpha)} \qquad (3.9)$$

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 more slowly. Then, the growth rate of agricultural sector will fall over time. 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.

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 values of $Z_{j\kappa_j}$ and κ_j. The parameter 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.

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

$$r + p^* = (1/s \cdot \zeta) \cdot \left(1 - \alpha/\alpha\right) \cdot P_{AGR}^{1/(1-\alpha)} \cdot A(E)^{1/(1-\alpha)} \cdot L^{(1-\alpha-\beta)/(1-\alpha)} \cdot H^{\beta/(1-\alpha)} \cdot \alpha^{2/(1-\alpha)} \qquad (3.10)$$

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

$$r + p^Z = (1/s \cdot \zeta) \cdot \left(1 - \alpha/\alpha\right) \cdot P_{AGR}^{1/(1-\alpha)} \cdot A(E)^{1/(1-\alpha)} \cdot L^{(1-\alpha-\beta)/(1-\alpha)} \cdot H^{\beta/(1-\alpha)} \cdot \alpha^{2/(1-\alpha)} - p^P \qquad (3.11)$$

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 ($r + p^Z$). The public sector affects the private sector's rate of return in two opposite directions. Through subsidy (s) and other activities that increase A(E), 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 the 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 as

$$Z_{j\kappa_j} = q^{(\kappa_j+1)\alpha/(1-\alpha)} \cdot \left[\left(\frac{1-\alpha}{\alpha}\right) \cdot P_{AGR}^{1/(1-\alpha)} \cdot A^{1/(1-\alpha)} \cdot L^{(1-\alpha-\beta)/(1-\alpha)} \cdot H^{\beta/(1-\alpha)} \cdot \alpha^{2/(1-\alpha)} - (r + p^P) \cdot (s \cdot \zeta)\right] \qquad (3.12)$$

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

$$Z = Q \cdot q^{\alpha/(1-\alpha)} \cdot \left[\left(\frac{1-\alpha}{\alpha}\right) \cdot P_{AGR}^{1/(1-\alpha)} \cdot A^{1/(1-\alpha)} \cdot L^{(1-\alpha-\beta)/(1-\alpha)} \cdot H^{\beta/(1-\alpha)} \cdot \alpha^{2/(1-\alpha)} - (r + p^P) \cdot (s \cdot \zeta)\right] \qquad (3.13)$$

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.

3.5 Testable Implications

Equation 3.13 represents the key relationship between aggregate private R&D (Z) and the various variables in the model. The first implication of equation 3.13 is that when the 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 $(1-\alpha)$ are taken as given in the model also.

The next variable is price of agriculture output (P_{AGR}), which is also positively related to level of R&D investment. A higher price of agriculture output increases the profit of final good producers, and the production of the final good. This increases the demand for intermediate goods and 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, and 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 sector's 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. In sum, the

net effect of public sector activities on level of private R&D spending is an empirical question that depends on the relative magnitude of these competing forces.

Chapter 4

EMPIRICAL MODEL

The quality innovation model developed in Chapter 3 shows the link between technical change and TFP. The sources of technical change are identified as public and private R&D investments, and increases in human capital of farmers. We now turn to testing the model using agricultural sector data for the U.S.

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 objective is to explore the factors that determine private agricultural R&D spending. After these issues are resolved, marginal internal rates of return to public and private R&D investments can be calculated based on the empirical results.

4.1 Implementation Issues

The conceptual model for the TFP equation is based on the equation 3.7, which is re-written here for expositional clarity.

$$Y = Q \cdot A(E)^{1/(1-\alpha)} \cdot P_{AGR}^{\alpha/(1-\alpha)} \cdot L^{(1-\alpha-\beta)/(1-\alpha)} \cdot H^{\beta/(1-\alpha)} \cdot \alpha^{2\alpha/(1-\alpha)} \qquad (3.7)$$

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 $\tilde{TFP}_t$ and the real value is $TFP_t = Q_t \cdot A(E)_t^{1/(1-\alpha)}$, then the relationship is $\tilde{TFP}_t = TFP_t + v_t$, with an additive error.

By this definition, changes in TFP are divided into their components.

$Q = \sum_{j=1}^{N} q^{\kappa_j \cdot \alpha/(1-\alpha)}$ is an aggregate quality index for the agricultural sector, while A(E) is the level of TFP not accounted by the quality index. The first component, Q is a stock of inventions available to producers. Q increases due to R&D efforts of public and private sector.

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 encompasses any activity that increases the human capital in the agricultural sector, including extension services carried out by the land-grant universities and education of farmers. Here, A(E) will be modeled as a function of extension services funds. This is also in line with previous empirical work that found the positive impact of extension funds (Huffman and Evenson (1993a).[14] A summary of the relationships of the variables in the model can be found in Figures 4.1 and 4.2.

4.1.1 How to measure and explain the Quality Index?

Since, the aggregate quality index (Q) is a measure of the stock of inventions, agricultural patent data will be used to measure Q. The patent data is total number of granted patents that are used by the agriculture sector[15]. As Q is a stock variable, a proxy for Q will be calculated from agricultural patents. The calculation of the stock variable is explained in the data section based on equations 4.12 and 4.13.

[14] Education is traditionally the variable of choice as a proxy for measuring human capital. But data on education level of farmers is unavailable for the period of this study. So, extension services funds are used as a proxy instead.

Patents provide a good, though imperfect, approximation to inventive activity and this type of data have been used before. Schmookler (1966) conducted one of the earlier studies in this area. He constructed data on patents relevant to a particular industry where his criteria was whether that industry benefited from the resulting product, rather than whether the industry created it. This study adopts a similar approach: it employs data on patents that are used by the agricultural sector.[16] One difference is that Schmookler used patent data as a proxy for inventive activity; an input to this process rather than an output. Huffman and Evenson (1993a) followed a similar approach and generated a data set of private R&D expenditures from agricultural patent data set and their approach also regards patents as an indicator of inventive activity. However, the aim of the current study is to understand the effects of technical change on measured productivity. So, patent data is used to measure technical change - i.e., an output of inventive activity.

More recently Schimmelpfennig and Thirtle (1999) used patent data to calculate private and public R&D stocks in the agricultural sector. Eaton and Kortum (1996) 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.

The patent data by industry is computed using information on the distribution of patenting across technology fields.[17] Caution should be exerted, however, when using patent data to measure technical change. 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

[15] The sectors included are livestock, crops and combo farms, fruits and vegetables, horticulture, service to livestock, service to crops, other.

inventiveness of sectors which protect many small inventions and underrepresent sectors which protect less but more important inventions. Third, not all patented inventions are adopted by farmers.

Griliches (1998) discusses trends in patenting and notes that trends in patent grants do not always follow trends of patent applications. "A patent is granted if it passes certain minimal standards of novelty and potential utility. These standards change over time. A change in the resources of the patent office or its efficiency will introduce changes in the lag structure of grants behind applications".

All these caveats suggest that there may be a discrepancy between the true quality index Q, and the observed quality index, Q*. This relationship is modeled here as $Q_t^* = Q_t + e_t$ - i.e., the 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 any sector increases Q. So, the empirical model for the quality index is proposed as follows:

$$\ln Q_t = h(\ln Z_t, \ln R_t) \tag{4.1}$$

where Z_t is private agricultural R&D spending and R_t is public agricultural R&D spending.

[16] As will be discussed later, the Johnson and Evenson data set also allocates patents according to industries of manufacture.
[17] For a discussion of this data set, see Johnson (1999).

4.1.2 TFP and technical change:

The quality innovation model establishes a direct and positive link between TFP and technical change. The empirical equation for TFP is proposed as

$$\ln TFP_t = g(\ln E_t, \ln Q_t, \ln R_t) \tag{4.2}$$

where E_t is extension funds, and Q_t is stock of patents, and R_t is public R&D spending. 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 new technology on TFP_t. In this specification, public and private R&D investments affect TFP_t indirectly through creation of new technology, which is captured by Q_t. R_t is also added as an explanatory variable to explore the possible direct effects of public R&D investments on TFP. Public R&D sector engages in different types of activities, and some of these activities may have a direct impact on TFP rather than an indirect effect through creation of new technology.

4.1.3 What determines private R&D investment?

The model also provides an analysis of private R&D investment (equation 3.13). When $TFP = Q \cdot A(E)^{1/(1-\alpha)}$ is plugged into this equation, and we take logs of both sides of the equation, we get[18]

$$\ln Z = A_1 + A_2 \cdot \ln P_{AGR} + A_3 \cdot \ln L + A_4 \cdot \ln H + A_5 \cdot \ln TFP + A_6 \cdot \ln Q + A_7 \cdot \ln r + A_8 \cdot \ln p^P + A_9 \cdot \ln s \tag{4.3}$$

where

$$A_1 = B_1 \cdot \ln q + B_2 \cdot \ln\left((1-\alpha)\cdot \alpha^{1/(1-\alpha)}\right) + B_3 \cdot \ln \zeta \tag{4.4}$$

The variable, Z, is private agricultural R&D investment. ζ, α, and q are constant.

The parameter s is the subsidy by public sector to private R&D sector and p^P is the probability of innovation by public sector. They correspond respectively to the complementary and substitute effects of public R&D spending. r is real interest rate. Land (L) and labor (H) inputs are correlated with TFP in the model and also in the estimation of TFP, so they are not included in the empirical specification for Z to avoid multicollinearity. The empirical equation for private R&D investment is proposed as

$$\ln Z_t = j(\ln R_t, \ln r_t, \ln TFP_t, \ln P_{AGRt}) \tag{4.5}$$

where R_t is public R&D spending corresponding to the variables s and p^P, and r_t is real interest rate. TFP_t is total factor productivity; and it corresponds to the total effect of A(E) and Q. P_{AGRt} is the price of output deflated by price of inputs, which will be proxied by an index of price received by farmers deflated by the GDP deflator.

4.2 Model Specification

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

$$\ln TFP_t = f(\ln E_t, \ln Q_t, \ln R_t) \tag{4.6}$$

(+) (+) (+)

$$\ln Q_t = g(\ln Z_t, \ln R_t) \tag{4.7}$$

(+) (+)

$$\ln Z_t = h(\ln R_t, r_t, \ln TFP_t, \ln P_{AGRt}) \tag{4.8}$$

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

---

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

The data used are in logs except ex-post real interest rate[19]. First, auto-correlation and partial auto-correlation functions of the variables were plotted and stationarity tests were conducted using the augmented Dickey-Fuller tests. The results that are shown in Appendix A Tables A.1-A.8 and Figures A.1-A.8 reveal that the variables in the system are all non-stationary. To make them stationary, all variables were first-differenced.[20]

Plots of auto-correlation and partial auto-correlation functions, as well as augmented Dickey-Fuller tests were used again to determine whether the log-differenced variables are non-stationary. Appendix A Tables A.9-A.15 and Figures A.9-A.15 show that all first differenced variables are stationary except the quality index. Because of the non-stationarity of $\Delta \ln Q$, I instead used once-lagged patents data (P_{t-1}) as a proxy for the incremental change in input quality as of year t. Unlike $\Delta \ln Q_t$, the patents data was found to be non-stationary.

The theoretical model assumed 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 into empirical analysis, lags of extension funds and public and private R&D investments were also 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 ((Huffman and Evenson (1992,1993a, 1993b), (Makki et al. (1999), Yee (1992)). Hence, lagged values of public R&D spending, private R&D spending, and extension funds were included.

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

[20] As first differenced log data is approximately equal to the growth rate, this specification is also in line with using a growth model as a framework for empirical analysis.

Different lag lengths beyond P_{t-1} were tried for the patent variable in the TFP equation, but likelihood ratio tests indicated that the additional lags were not warranted. The equations for $\Delta \ln TFP_t$, $\ln P_t$ and $\Delta \ln Z_t$ were set up based on these concerns. The optimal lag lengths for the explanatory variable beyond period t-1 were chosen using the Likelihood Ratio test.

The final system of equations is as follows:

$$\Delta \ln TFP_t = f(\sum_{i=0}^{k} \Delta \ln E_{t-i}, \ln P_{t-1}, \sum_{i=1}^{l} \Delta \ln R_{t-i}) \tag{4.9}$$

$$\ln P_t = g(\sum_{i=1}^{m} \Delta \ln Z_{t-i}, \sum_{i=1}^{n} \Delta \ln R_{t-i}) \tag{4.10}$$

$$\Delta \ln Z_t = h(\sum_{i=0}^{p} \Delta \ln R_{t-i}, \Delta r_t, \sum_{i=1}^{r} \Delta \ln TFP_{t-i}, \Delta \ln P_{AGRt}) \tag{4.11}$$

The three dependent 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_{AGRt}), ex-post real interest rate (Δr_t), public R&D spending (ΔR_{t-i}), and private R&D spending (ΔZ_{t-i}). As all right hand side variables are pre-determined, there was no need to use instrumental variables to correct for statistical endogeneity (as would be the case if contemporaneous observations of the endogenous variables were to appear on the right hand side. However, there is ample reason to suppose, a priori, that the error terms of the three equations are correlated. Hence, to improve the efficiency of the parameter estimates, the system was estimated as a system of seemingly unrelated regressions.

4.3 DATA[21]

Tables 4.1 and 4.2 provide an overview of data sources, data description and summary statistics for key variables in the model. Total Factor Productivity estimates for the U.S. agricultural sector (Figure 4.3) 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. It corresponds to a functional form for aggregator function that can provide a second order approximation to an arbitrary twice-differentiable linearly homogenous function.

Public agricultural R&D spending data (Figure 4.4) 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.[22]

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. USDA Intramural Research consists of funds provided by USDA to Agricultural Research Service, Forest Service, Economic Research Service, National Agricultural Library. USDA Extramural research funds consist of funds

[21] A summary of data section is presented in Table 4.1 and summary statistics are presented in Table 4.2.
[22] 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)). Research activity uses a different set of goods than the bundle of goods included while calculating CPI or GDP deflator. Adjusting nominal research expenditures by CPI and GDP deflator may overstate the trend in real research spending over time. Klotz et al. constructs a Research Deflator following the methodology developed in Pardey et al. (1989).

that are provided by USDA to SAES. These funds include USDA Formula Funds and USDA Project Support funds. Other federal funds for SAES include funds from National Institutes of Health, National Science Foundation, US Agency for International Development, Department of Defense, Department of Energy, NASA, Tennessee Valley Authority, Department of Health and Human Services and other non-USDA services. The second category of public R&D spending includes state funds given to SAES and cooperating institutions. These funds are given to SAES, 1890 schools, forestry schools and veterinary schools. The third category includes funds given by private sector to state institutions through direct grants, product purchases, patent license fees, and other sources.

Private agricultural R&D spending data (Figure 4.5) were estimated by Klotz, Fuglie and Pray (1995) and these are provided on the USDA ERS website. The series is in thousands of 1996 dollars converted from current dollars by Research Deflator. Figure 4.6 disaggregates the private R&D data. 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 (Figure 4.7) 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 (Figure 4.8) 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. Therefore, these data are of limited use for economic analysis conducted in this study.[23]

YTC was designed to translate these IPC definitions of patents to Industries of Manufacture (IOM) and Sectors of Use (SOU).[24] To achieve this aim, YTC uses the information from patents granted in Canada. Canadian Intellectual Property Office assigns a technology field from IPC system to each patent it issues. At the same time, it also assigns an IOM and a SOU to each patent. YTC uses the probability distributions of each IPC or product code across IOM's and SOU's to assign probable IOM's and SOU's to any patent whose IPC is known. The conditional probabilities that are estimated from Canadian data are applied to patents in other countries or time periods, where only the technology fields of these patents are known.

WTC was developed by Johnson as a concordance between U.S. Patent Classification system and the internationally standard IPC. It uses information from

[23] 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.

[24] 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.

patents granted in the U.S. to build a concordance between USPC and IPC systems with the probability that any given patent in a particular USPC will fall into a particular 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.

The patent data set used in this study was 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. It bears pointing out that the data (depicted in Figure 4.8) demonstrate a highly regular cyclical pattern.

The quality index was created as a stock variable from data on the number of agricultural patents. To do this, the Perpetual Inventory Method according to the following formulae:[25]

$$Q_{t+1} = Q_t \cdot (1-\delta) + P_{t+1} \tag{4.12}$$

$$Q_0 = P_0\left(\frac{1+g}{g+\delta}\right) \tag{4.13}$$

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.

The ex-post real interest rate (r_t) was calculated according to the following formula:

$$r_t = n_t - \left(\frac{D_{t+1} - D_t}{D_t} * 100\right) \tag{4.14}$$

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

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.

Finally, an index of prices received by farmers was used as a proxy for P_{AGR}. These data were obtained from USDA NASS. They include all farm products, and are deflated by the GDP deflator.

Table 4. 1. Data Source and Variables (1960-1996)

Variable Name	Variable Definition
TFP	*Multifactor productivity index of the ratio of aggregate crop and livestock production to aggregate production inputs*
Public R&D Spending (R)	*SAES spending plus USDA spending*
Private R&D Spending (Z)	*Agricultural Research Expenditures by Private Sector (Agricultural Inputs + Food & Kindred Products R&D)*
Agricultural Inputs R&D Spending	*Private sector R&D spending on Plant Breeding, Veterinary Pharmaceuticals, Farm Machinery, Agricultural Chemicals*
Extension Funds (E)	*Funds for Cooperative Extension Service (federal, state, county)*
Patents (P)	*Total number of patents granted in US by sector of use as agriculture*
Quality Index (Q)	*Stock variable calculated from agricultural patents*
Price received (P_{AGR})	*Index of price received- all farm products deflated by GDP deflator*
Nominal Interest Rate	*Annual interest rate on 1 year Treasury Bills*
Real Interest Rate (r)	*Nominal interest rate – ex post inflation rate (CPI)*
Research Deflator	*USDA ERS estimates by Klotz, Fuglie and Pray*

Table 4. 2. Summary Statistics

Variable	N	Mean	Std.Dev.	Min.	Max.
Public R&D	37	2,612,353.67	580,510.16	1,579,149.08	3,333,191.38
Private R&D	37	2,655,572.49	873,876.76	1,368,222.71	3,996,160.65
Extension Funds	37	1,332,475.76	246,037.12	734,140.15	1,610,679.44
TFP	37	68.17	16.04	45.62	100.00
Patent	37	6,012.40	1,971.75	2,148.10	9,151.53
Price Received ($)	37	66.31	24.01	33.29	100.00
Interest Rate	37	0.016	0.026	-0.038	0.078
U.S. GDP	37	5,182,087,805	1,910,930,155	2,376,700,000	9,224,000,000

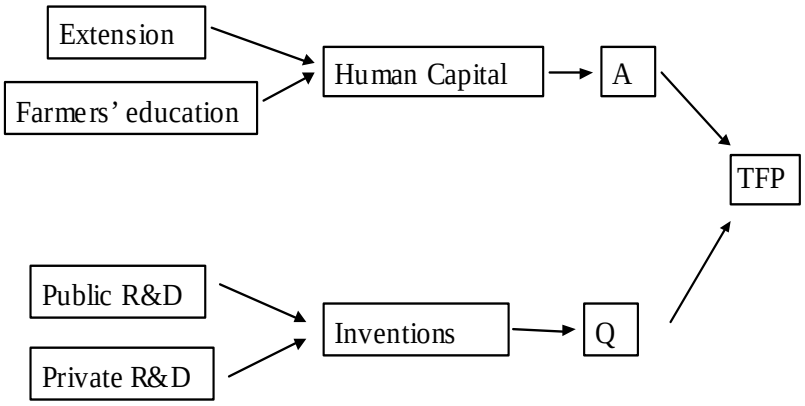

Figure 4.1. Components of TFP

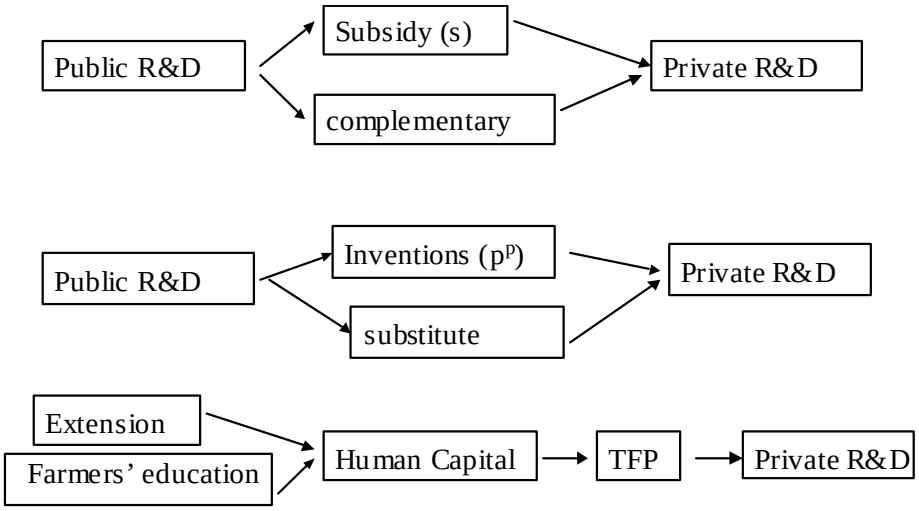

Figure 4.2. Factors that affect Private R&D

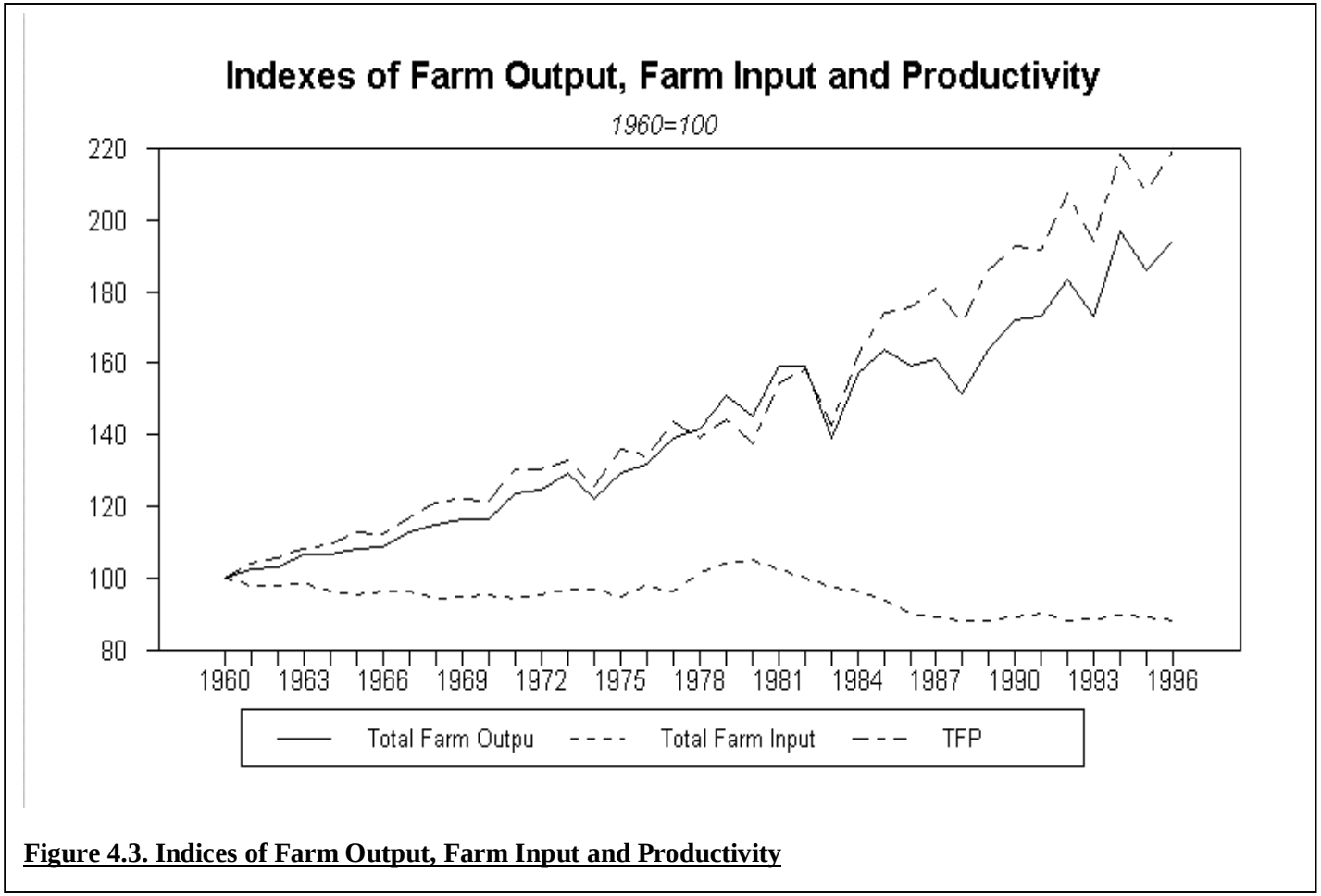

Figure 4.3. Indices of Farm Output, Farm Input and Productivity

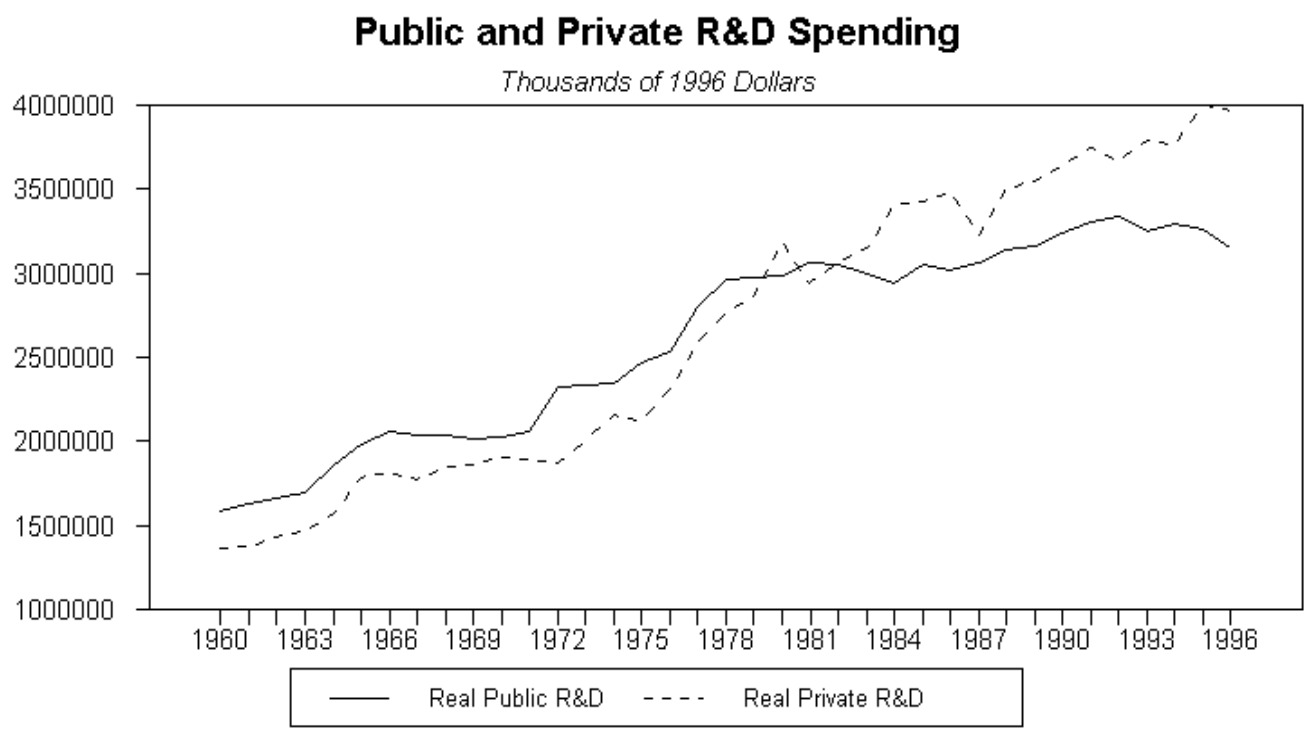

Figure 4.4 Public and Private Agricultural R&D Spending (Thousands of 1996 dollars)

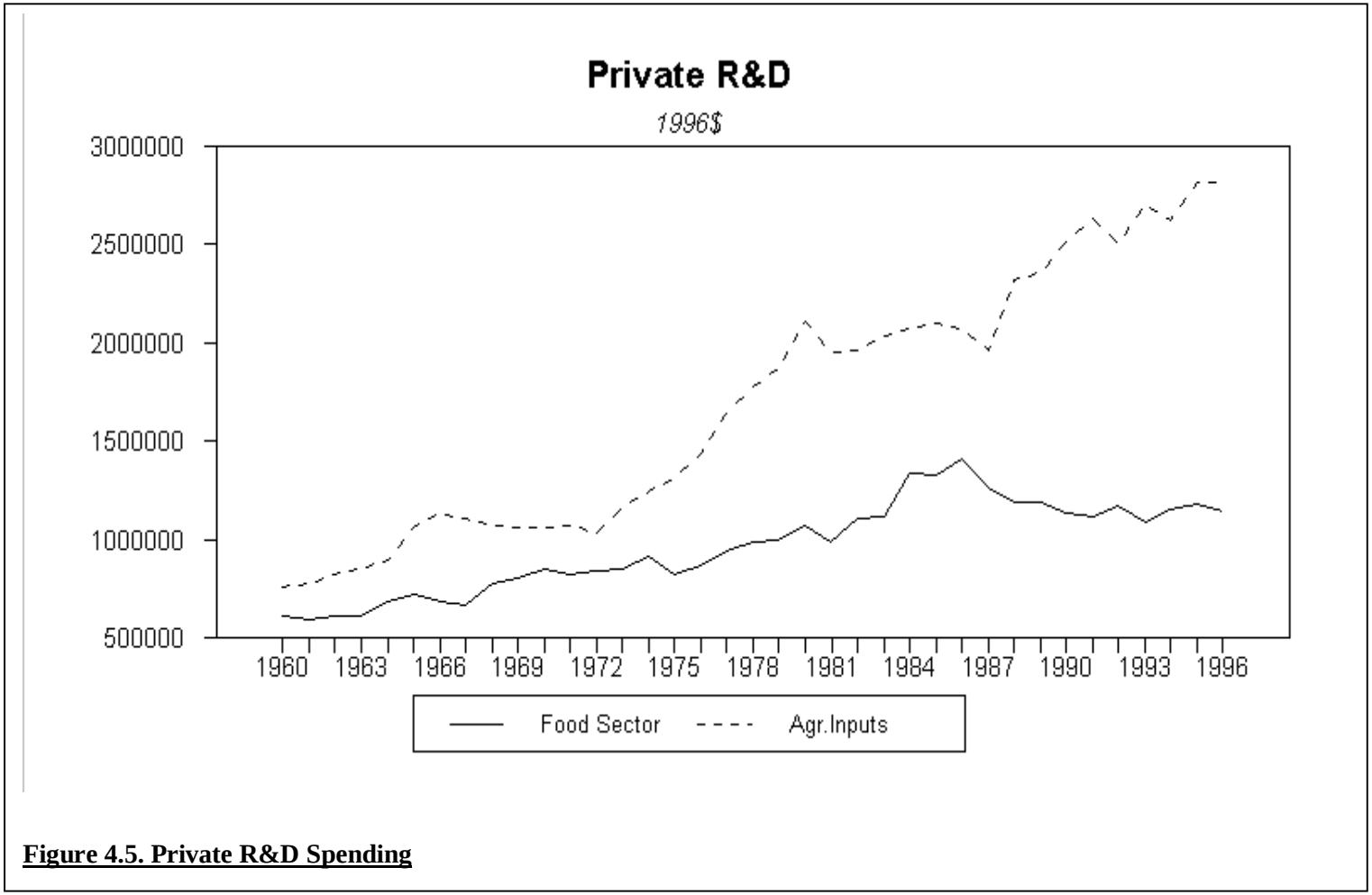

Figure 4.5. Private R&D Spending

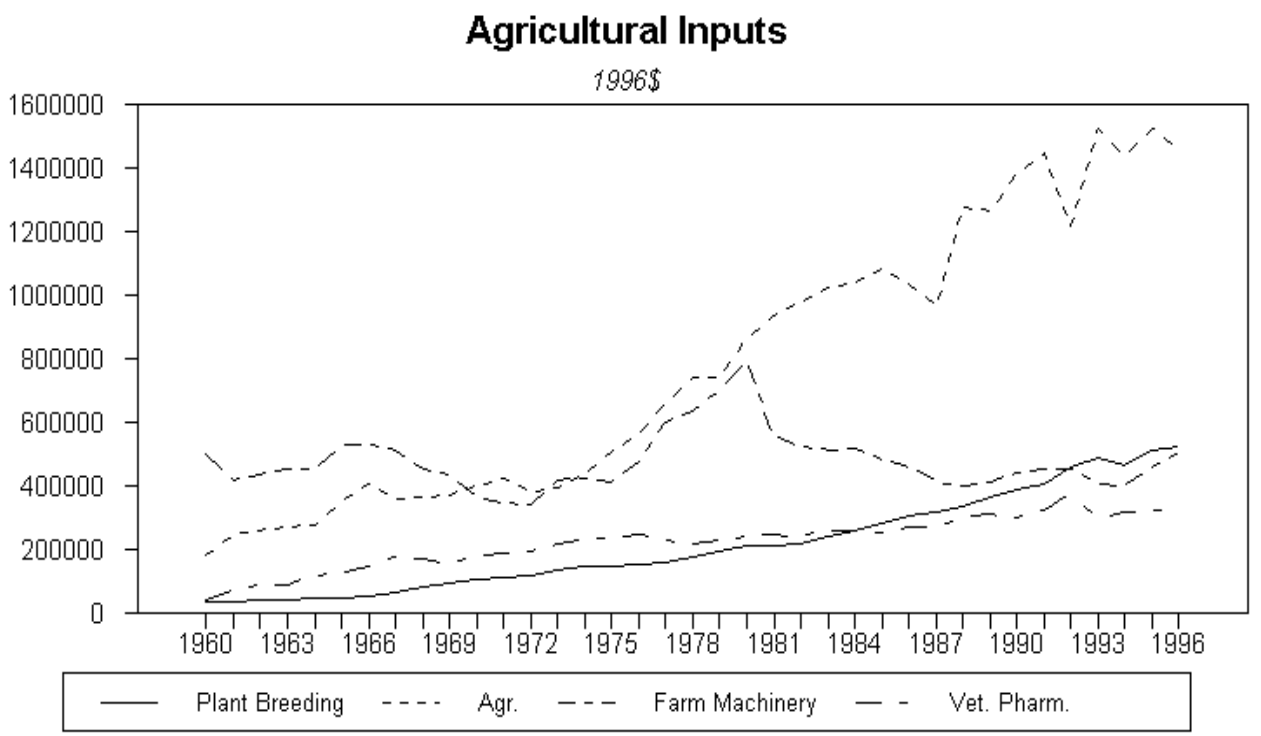

Figure 4.6. Agricultural Inputs R&D Spending

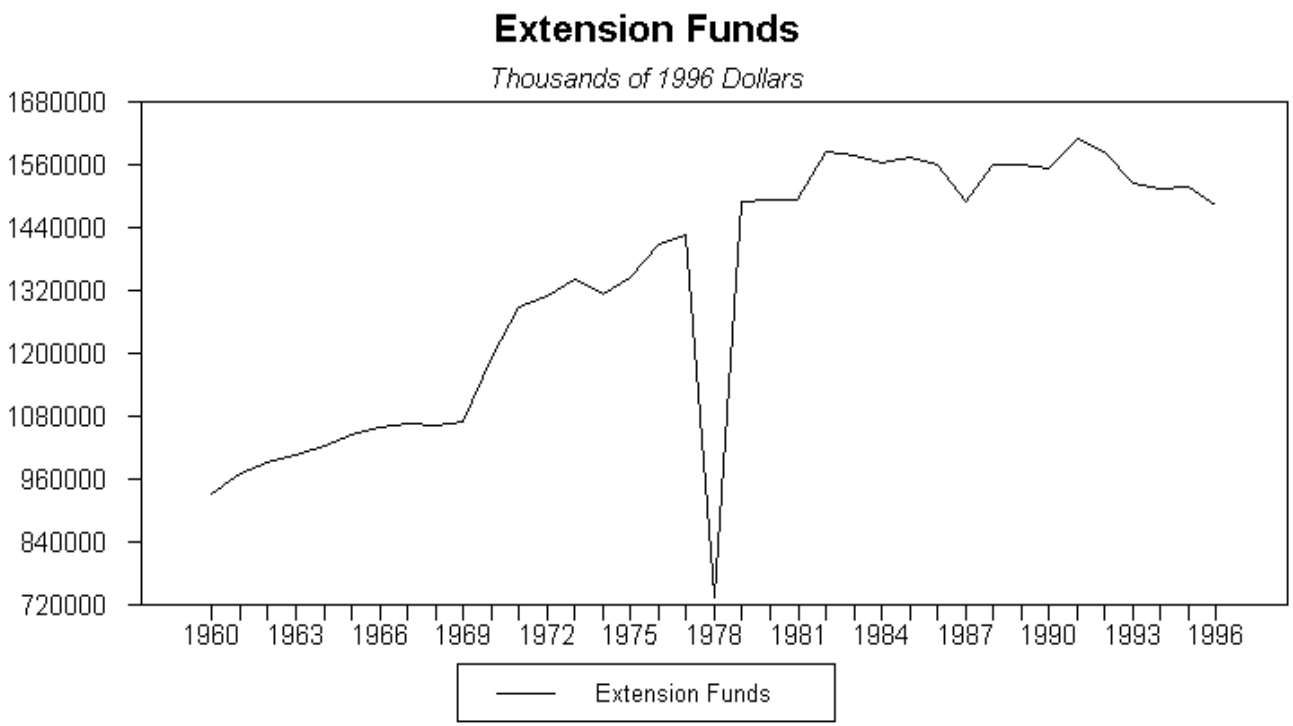

Figure 4.7. Extension Services Funds

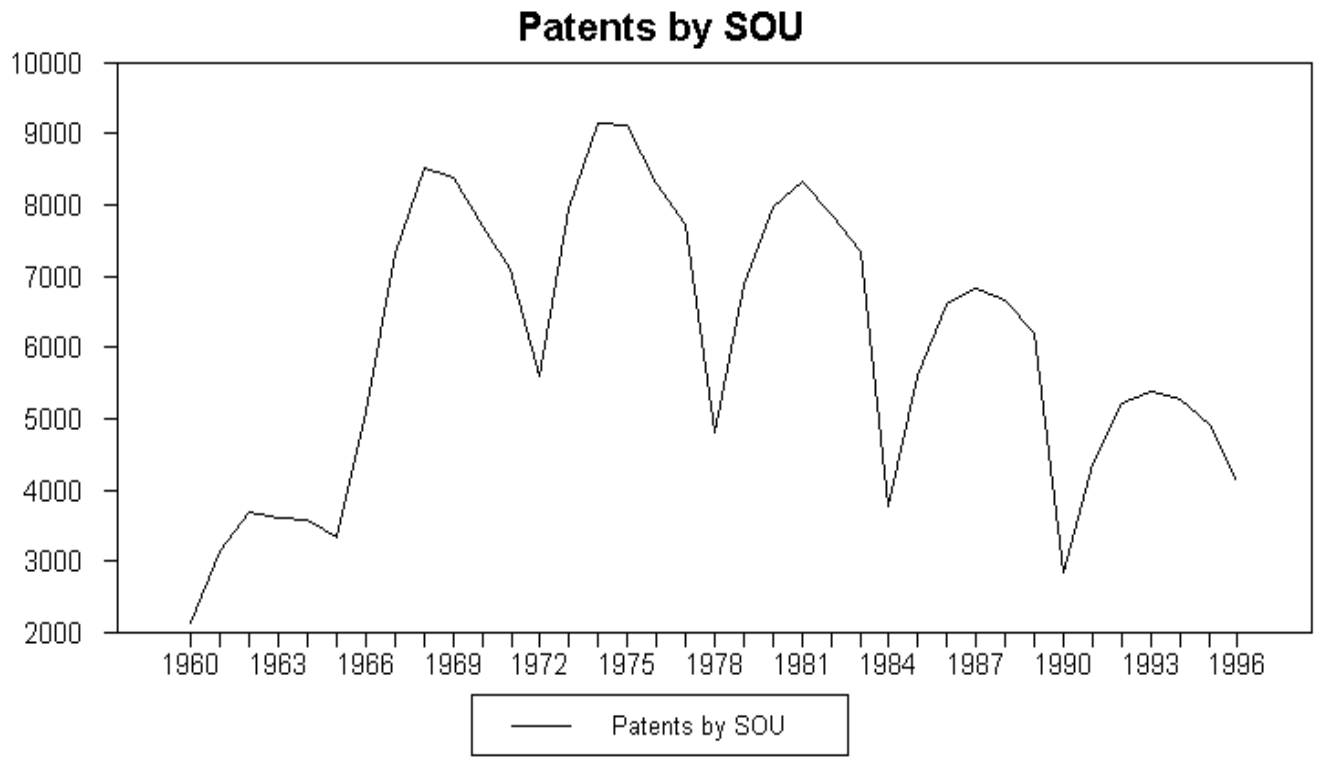

Figure 4.8. Agricultural Patents

Chapter 5

EMPIRICAL RESULTS

5.1 Choosing the Lag Lengths

Equations 4.9, 4.10 and 4.11 were first estimated separately with ordinary least squares and Likelihood Ratio (LR) tests were used to choose the optimal lag lengths for the explanatory variables. Using LR tests allows the data to tell the optimal lag length. This is different from previous studies that simply impose a lag structure in an ad hoc manner. To choose the optimal lag length, first each equation was estimated with a large number of lags for explanatory variables, and at each step the LR test was conducted on the last lag of each variable. If the LR test accepted the null hypothesis that the coefficient estimate was not significantly different from zero, the last lag was dropped and the equation was estimated again until the LR test rejected the null hypothesis.

The results with ordinary least squares (OLS) estimation are shown in Table 5.1 For the TFP equation, LR tests indicated that two lags for extension funds, zero lags for patent and seven lags for public R&D investment are optimal. Current extension variable is included in the TFP equation as extension activities may affect TFP in the same period. However, for public R&D variable the optimal lag length was chosen starting from period t-1, as public R&D expenditures will have an impact on TFP with a lag.

$$\Delta \ln TFP_t = \alpha_0^T + \sum_{i=0}^{2} \alpha_i^T \cdot \Delta \ln E_{t-i} + \beta^T \cdot \ln P_{t-1} + \sum_{i=1}^{7} \gamma_i^T \cdot \Delta \ln R_{t-i} \qquad (5.1)$$

For the patent equation, LR tests showed three lags for public R&D spending and three lags for private R&D spending are optimal. Again, the optimal lag length was chosen for these variables starting in period t-1. In other words, the model for patents was

specified as

$$\ln P_t = \alpha_o^P + \sum_{i=1}^{3} \alpha_i^P \cdot \Delta \ln R_{t-i} + \sum_{i=1}^{3} \gamma_i^P \cdot \Delta \ln Z_{t-i} \qquad (5.2)$$

For the private R&D spending equation, LR tests revealed that the model with five lags for public R&D spending and six lags for TFP is optimal. Current public R&D variable is included in this equation. However, lag lengths for TFP were chosen start at t-1. The model for private R&D spending is chosen as

$$\Delta \ln Z_t = \alpha_o^Z + \sum_{i=0}^{5} \alpha_i^Z \cdot \Delta \ln R_{t-i} + \sum_{i=1}^{6} \gamma_i^Z \cdot \Delta \ln TFP_{t-i} + \delta \cdot \Delta r_t + \varepsilon \cdot \Delta \ln P_{AGRt} \quad (5.3)$$

5.2 SUR Results

The SUR results for the system of equations are presented in Table 5.2. For the total factor productivity equation, results indicate a positive relationship between extension expenditures and total factor productivity growth. The evidence suggests that this positive effect occurs over time, as only the coefficient of ΔE_{t-2} is significant. For the public R&D variables, only the longest lags (ΔR_{t-6} and ΔR_{t-7}) were significant. Interestingly, they were of different signs with the sum of the parameter estimates for these two variables being positive. Thus, a positive overall effect of public R&D on TFP is revealed. The results indicated no significant relationship between patents and TFP. Indeed, the sign of the coefficient on the patents variable was negative, contrary to the prediction of the model. This is an unfortunate result, but in all likelihood is due to the nature of the patent data. Recall that this data demonstrated a highly cyclical nature (see Figure 4.8). Some cyclicality in patents would not be unexpected, given that important

scientific breakthroughs often give rise to a flurry of smaller, but nonetheless patentable, innovations in their aftermath. However, the regularity of the cycles evident in Figure 4.8 raises some suspicions about the way in which the patent data was constructed.

In the patent equation, evidence was found of a significant positive relationship between patents and private R&D variables. The coefficients on the first two lags of private R&D were of the wrong sign, but not significant. The third lag was significant, however, and of the predicted sign. The results also point to a positive relationship between patents and public R&D expenditures. All of the parameter estimates were positive. None were significant at the 10% level, although the p-value of the ΔR_{t-3} was 0.11.

Results from the private R&D equation indicate that public R&D has a positive relationship with private R&D. The significance of the 5^{th} lagged term – coupled with the non-significance of the other lags – indicates that this influence takes place, but only after some period of time. The combined effects – i.e., the sum of all the lags – is positive. Thus, public R&D is found to be complementary to private R&D. The coefficients on both the interest rate and agricultural output price variables are of the predicted sign, but not significant. The coefficients on the various lags of TFP are uniformly of the wrong sign, but also are not significant.

Taken together, the regression results offer substantial support for the predictions of the theoretical model. The signs of the parameter estimates are generally in line with what the theory predicts, and the precision of the estimates is such that many of the hypothesized relationships are found to be statistically significant. A notable, and

unfortunate, exception to this involves the estimated relationship between the patents variable and TFP.

5.3 Reduced form Estimates

The fact that the coefficient on the patent variable was negative (albeit not significant) precludes estimating rates of return to research from the SUR estimates. This is because such an exercise would require using the estimated relationship between ΔTFP and P_{t-1} in calculating the marginal products of both private and public R&D. Thus, in order to generate estimates of internal rates of return, a reduced form equation for ΔTFP were estimated.

The optimal lag lengths for the explanatory variables were chosen by the likelihood ratio tests. Current extension variable was included in the total factor productivity equation, whereas public and private R&D variables started beyond period t-1. The total factor productivity equation is specified as follows:

$$\Delta \ln TFP_t = \alpha_0^T + \sum_{i=0}^{2} \alpha_i^T \cdot \Delta \ln E_{t-i} + \sum_{i=1}^{7} \gamma_i^T \cdot \Delta \ln R_{t-i} + \sum_{i=1}^{5} \beta_i^T \cdot \Delta \ln Z_{t-i} \qquad (5.4)$$

The results from ordinary least squares estimation for the reduced form are presented in Table 5.3. The coefficient estimates for the extension variables are all insignificant, though the evidence suggest that the overall effect is positive as the sum of the coefficient estimates is positive. Only the last two lags of public R&D variables are significant, although they are of opposite sign. The combined effect of public R&D on total factor productivity is positive as the coefficient estimates of these variables add up to a positive number. Only the coefficient estimate of the current private R&D variable is

significant, and its sign is positive as the theory predicted. Surprisingly, lagged private R&D variables are not significant. This may be due to the nature of the private R&D data set used in this study. Current private R&D variable may pick up the impact of advertisement of new products by R&D firms, which may also be included in the R&D expenditures reported by these firms. The combined effect of private R&D on TFP is positive as the sum of the coefficient estimates is positive.

5.4 Internal Rates of Return to R&D

The final step in the evaluation of the public and private R&D activities in the U.S. is calculating rates of return to those activities. This method compares the streams of changes in research benefits with the streams of changes in research costs that produced them by using capital-budgeting methods. The results are summarized as internal rates of return. In this study, marginal internal rates of return are calculated, that is actual research and a change from actual research are compared, rather than actual research and zero research. Using this analysis, we can answer the question of how beneficial it is for a society to invest its resources in agricultural research and extension activities. This type of analysis may help the efficient allocation of society's scarce resources among alternative uses. An additional benefit is that it gives information about the magnitude of rates of return to public and private R&D and help the discussions on the optimal role of public sector in agricultural R&D.

There have been numerous studies that estimated the rates of return to R&D and extension. Most of these studies have found rather high rates of return, in excess of at least 20 percent. These findings have been widely criticized in the literature, on the

grounds that these rates of return exceed the observed markets rates of return on alternative investments (Makki, Thraen, and Tweeten (1999), Alston and Pardey (1996)). Malkeil (1990) reported that the rate of return on long-term assets in the U.S. is about 10 percent.

Table 5.4 summarizes the findings in the literature. There have been different approaches adopted in the process of re-estimating rates of return to R&D. Huffman and Evenson (1993) included private R&D spending in their estimations and find the IRR to public R&D as 41 percent and to private R&D as 46 percent. Yee (1992) followed a similar approach but a different private R&D spending data set and estimated a 49 percent rate of return to public R&D and 38 percent rate of return to private R&D. Chavas and Cox (1992) employed a non-parametric approach and found the IRR to public R&D as 28 percent and to private R&D as 17 percent. Makki, Thraen and Tweeten (1999) corrected for stationarity in the data and reported an IRR of 27 percent for public R&D and 6 percent for private R&D using a cointegration and error correction model framework.

Alston and Pardey (1996) also voiced their suspicion that overestimation may have predominated and claimed that understating the costs, overstating the benefits and predetermining the research lag structure may be some of the reasons as to why these rates of return are quite high. They also conducted a sensitivity analysis of rates of return and showed that estimated rates of return are sensitive to the lag distribution and the timing of the benefits from research. Alston, Marra, Pardey and Wyatt (2000) conducted a meta-analysis of returns to agricultural R&D based on a comprehensive data set of previous studies to understand the large differences in the estimated rates of return. They

claimed that the type of research evaluated and the choice of lags partly explain the wide disparity among estimated rates of return.

Marginal internal rates of return to public R&D investment and private R&D investment are calculated following the approaches described in Davis (1981), Yee (1992), and Alston, Norton and Pardey (1995). To calculate the rates of return, the reduced form coefficient estimates are used.

As the functional form used in the estimations is log function, these coefficient estimates are elasticities. In the next step, marginal products of research and extension activities are obtained.

Let me give an example of how marginal products are calculated for public R&D from average products.

$$\frac{\partial TFP_t}{\partial R_{t-i}} \cdot \frac{R_{t-i}}{TFP_t} = \frac{\partial \ln TFP_t}{\partial \ln R_{t-i}} = \alpha_2 \cdot \beta_{1i} + \alpha_{3i} \tag{5.5}$$

$$\frac{\partial TFP_t}{\partial R_{t-i}} = MP(R_{t-i}) = (\alpha_2 \cdot \beta_{1i} + \alpha_{3i}) \cdot \frac{TFP}{R} \tag{5.6}$$

The average products used in the calculation of MP's are geometric means of first differenced data (Davis (1981)).[26] The values for variables other than TFP are all deflated so that inflation does not affect the calculation of MIRR. After MP's are calculated, value marginal products are calculated following the approach adopted in Yee (1992) according to the following formula:

$$\frac{\partial Y_t}{\partial R_{t-j}} \equiv VMP_{t,t-i} = MP \cdot \frac{\partial Y_t}{\partial TFP_t} \tag{5.7}$$

[26] TFP_{GM}=1.92, $(\text{public R\&D spending})_{GM}$=41,129.47, $(\text{private R\&D spending})_{GM}$=71,831.71, and $(\text{extension funds})_{GM}$=20,958.17.

where Y_t is value of agricultural output. The value for $\frac{\partial Y_t}{\partial TFP_{t-i}}$ is the slope coefficient when Y_t (value added to the U.S. economy by the agricultural sector via the production of goods and services, deflated and in thousand dollars) is regressed on TFP, which is found as 1,101,355.

Marginal internal rate of return is the discount rate that yields a net present value of zero. After MP's and VMP's are calculated for private R&D, public R&D and extension variables, the following formula for MIRR is used:

$$\frac{\sum_{i=0}^{L} VMP_i}{(1+r)^L} - 1.00 = 0 \qquad (5.8)$$

This approach assumes that all the benefits occur in one particular year. This method is used in Griliches (1964) but L was chosen as one. Davis (1981) proposed that L should be the mean lag of the distribution of the benefits.

In this study, there were two methods used to choose L. First, only the coefficient estimate that was significant in the TFP equation is used to calculate MP's and VMP's. MIRR is then calculated from these values with L as the lag length that the coefficient estimate used was significant. For the extension variable, the coefficient estimate for ΔE_{t-2} is used as it is the closest one to being significant. The rate of return for public R&D is -7 percent as the sum of the two significant variables is very small, as one of them is negative. The rate of return for private R&D is 1696 percent, which is surprisingly high. The reason for this finding is the fact that the impact of private R&D on total factor productivity is significant only at current lag, which implies that there is no time period between research and the benefits from research. The rate of return for extension is

calculated as 128 percent.

Secondly, the overall impact of R&D and extension variables is used to calculate rates of return. To do that, the sum of the coefficient estimates and the last lag of these estimates are used to calculate MP's and VMP's. This method reveals no rate of return to public R&D as the sum of the coefficient estimates for public R&D is negative. The rate of return to private R&D is 50 percent, which is much smaller than the previous rate of return calculated. This is due to the lower value of MP's and VMP's used and the longer lag length that was chosen for L. The rate of return to extension is calculated as 105 percent, which is somewhat smaller than the previous one.

TABLE 5. 1. OLS REGRESSION RESULTS[a]

	Dependent Variable		
Variable	ΔTFP	Patents	ΔPrivate R&D
Intercept	0.224(0.422)	8.650(0.075)**	0.042(0.061)
ΔE(t)	-0.088(0.102)		
ΔE(t-1)	0.019(0.096)		
ΔE(t-2)	0.157(0.083)*		
P(t-1)	-0.023(0.049)		
ΔR(t)			-0.221(0.337)
ΔR(t-1)	-0.534(0.393)	1.360(1.665)	0.253(0.482)
ΔR(t-2)	-0.0002(0.420)	0.928(1.751)	0.447(0.313)
ΔR(t-3)	0.059(0.403)	2.734(1.696)	0.227(0.366)
ΔR(t-4)	0.177(0.402)		-0.413(0.355)
ΔR(t-5)	0.211(0.413)		0.578(0.347)
ΔR(t-6)	-0.853(0.458)*		
ΔR(t-7)	0.917(0.448)*		
ΔZ(t-1)		-1.027(1.159)	
ΔZ(t-2)		-1.212(1.226)	
ΔZ(t-3)		2.327(1.071)*	
ΔTFP(t-1)			-0.117(0.297)
ΔTFP(t-2)			-0.564(0.488)
ΔTFP(t-3)			-0.203(0.586)
ΔTFP(t-4)			-0.082(0.542)
ΔTFP(t-5)			-0.130(0.403)
ΔTFP(t-6)			-0.317(0.287)
Δr			-0.547(0.734)
ΔP_{AGR}			0.103(0.179)
R^2	0.403	0.360	0.510

a. These are ordinary least squares regression estimates. Standard errors are in parentheses. ** and * denote significance at the 0.05 level and 0.10 level respectively.

TABLE 5. 2. SUR REGRESSION RESULTS[a]

	Dependent Variable		
Variable	ΔTFP	Patents	ΔPrivate R&D
Intercept	0.171(0.421)	8.654(0.075)**	0.037(0.061)
ΔE(t)	-0.080(0.102)		
ΔE(t-1)	0.018(0.096)		
ΔE(t-2)	0.152(0.082)*		
P(t-1)	-0.017(0.049)		
ΔR(t)			-0.164(0.332)
ΔR(t-1)	-0.521(0.393)	1.388(1.664)	0.335(0.478)
ΔR(t-2)	-0.020(0.419)	0.998(1.750)	0.435(0.312)
ΔR(t-3)	0.045(0.403)	2.804(1.694)	0.160(0.364)
ΔR(t-4)	0.180(0.402)		-0.366(0.351)
ΔR(t-5)	0.195(0.412)		0.645(0.343)*
ΔR(t-6)	-0.841(0.456)*		
ΔR(t-7)	0.876(0.447)*		
ΔZ(t-1)		-1.132(1.150)	
ΔZ(t-2)		-1.293(1.217)	
ΔZ(t-3)		2.239(1.063)**	
ΔTFP(t-1)			-0.147(0.293)
ΔTFP(t-2)			-0.515(0.481)
ΔTFP(t-3)			-0.143(0.579)
ΔTFP(t-4)			-0.047(0.535)
ΔTFP(t-5)			-0.117(0.398)
ΔTFP(t-6)			-0.344(0.283)
Δr			-0.466(0.724)
ΔP_{AGR}			0.075(0.177)

a. These are seemingly unrelated regression estimates. Standard errors are in parentheses. ** and * denote significance at the 0.05 level and 0.10 level respectively. System weighted R^2 is 0.4247.

TABLE 5. 3. OLS REGRESSION RESULTS FOR REDUCED FORM[a]

	Dependent Variable
Variable	ΔTFP
Intercept	0.016(0.021)
ΔE(t)	-0.047(0.108)
ΔE(t-1)	0.014(0.097)
ΔE(t-2)	0.118(0.084)
ΔR(t-1)	-0.538(0.392)
ΔR(t-2)	-0.335(0.458)
ΔR(t-3)	-0.115(0.448)
ΔR(t-4)	0.237(0.440)
ΔR(t-5)	0.228(0.429)
ΔR(t-6)	-0.891(0.469)*
ΔR(t-7)	0.902(0.466)*
ΔZ(t-1)	0.610(0.291)*
ΔZ(t-2)	0.086(0.309)
ΔZ(t-3)	-0.082(0.295)
ΔZ(t-4)	-0.034(0.321)
ΔZ(t-5)	-0.187(0.274)
R^2	0.589

a. These are ordinary least squares regression estimates. Standard errors are in parentheses. ** and * denote significance at the 0.05 level and 0.10 level respectively.

Table 5. 4. RATES OF RETURN IN THE LITERATURE

Variable	Public R&D	Private R&D	Extension	Time Period	Estimation Procedure
Present Study	-7%	50-1696%	105-128%	1960-96	SUR
Makki, Thraen, Tweeten (1999)	27%[a]	6%		1930-90	Cointegration/ECM
Chavas and Cox (1992)	28%	17%		1950-82	Non parametric
Huffman and Evenson (1993)	41%	46%		1950-82	Zellner's SUR
Huffman and Evenson (1989)	62%	0%[b]		1949-74	Zellner's SUR
Yee (1992)	49%	38%		1915-85	Polynomial distributed lag
Davis (1981)	28-52%	c		1964-74	Polynomial distributed lag
Cline (1975)	41-50%	c		1939-72	Polynomial distributed lag
Griliches (1964)	300%	c		1949-59	Production function

a. Public R&D and extension are included together.
b. Estimates were slightly negative or near zero.
c. No estimates available.

Chapter 6

SUMMARY AND CONCLUSIONS

This study 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 commercially motivated efforts of researchers responding to economic incentives and a public research and development sector. The link between total factor productivity and technical change was explored in the model. TFP growth was separated into an invention component and a human capital component. 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 also included a mechanism that explored the relationship between technical change and research carried out in the public and private domain. In the model, public and private R&D sectors directly affect creation of new technology (inventions), 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 relationship between these sectors is explored at the same time.

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 modeled as a possible substitute to private R&D sector as it engaged 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 was ambiguous in the model.

One important feature of the model is that private R&D spending is endogenously determined in the economic system. As technical change depends on R&D activities, this model claims that technical change and productivity growth are both determined endogenously in the economic system. This is one key distinction from the previous empirical research. Previously when analyzing the impacts of technical change on productivity, all these new products, new processes or newly acquired skills were combined into an increase in the knowledge stock that increases the productivity. Although, R&D sector is critical to the process of technical progress, the economics determining R&D investment were not analyzed theoretically. Furthermore, when estimating the impact of R&D on TFP, R&D spending was considered to be exogenously determined. However, the model developed here shows that if the possible simultaneous relation between TFP and R&D investments is not considered, the parameter estimates may be inconsistent. That may be one of the reasons why the estimated rates of returns to research reported in the literature are much higher than the observed market rates of return on alternative investments.

In the model, both private firms and public sector conduct R&D to create intermediate goods of higher quality that are used in the production of final good. One critical assumption is that the motivation for 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. Starting in 1970, the scope and the strength of patent protection have been expanded in the U.S.

Traditionally, the public sector has dominated agricultural R&D in the U.S. and provided farmers many innovations that increased agricultural output. Although, private R&D activities in agriculture had a lesser role, real private R&D spending has surpassed real public R&D spending in the last two decades. Changes in the level and the composition of both public and private R&D spending require rethinking the division of labor between these two sectors. Different factors were identified as possible reasons for the increasing role of private sector in agricultural R&D, such as changes in property rights and advances in biotechnology.

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 has weakened. An example of this is the case of plant breeding R&D, where the 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 such role that has been identified is providing access to the knowledge created by private firms for the whole society to benefit. Another role for public sector is basic science research. Other similar public roles are identified as research in minor crops, germplasm preservation and development, education of R&D personnel and farmers, extension activities, environmental and food safety regulations. As the quality innovation model employed in this study explores the relation between public and private R&D

sectors, it provides a fruitful framework to discuss the optimal role of public sector in agricultural R&D and generates some guidelines in terms of the optimal allocation of scarce resources for a society.

U.S. agriculture sector also benefits widely from the extensive extension services carried out through the country. These activities are influential in facilitating the spread and adoption of new techniques and processes. The model also takes this structure into account and includes extension services into the model as a factor that increases human capital in the sector, and in turn influences TFP.

In the empirical analysis, the propositions of the model were tested using the U.S. agricultural sector data for the period 1960-1996. 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. A patent production function was estimated with inputs as public and private agricultural R&D spending. Finally, the determinants of private agricultural R&D spending were explored.

In the empirical specification, lagged 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. 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 as a sytem of seemingly unrelated regressions (SUR). The estimation methodology adopted increased the efficiency of parameter estimates, by taking account of cross equation correlations

between error terms. In addition, the data was also made stationary by first differencing it to avoid spurious regression.

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 generally consistent with the theoretical predictions of the quality innovation model. Public R&D and extension variables were found to have positive impact on TFP growth, as predicted by the theory. Current and past public and private R&D investments in agricultural sector were found to have a 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 is important for technological progress in the U.S. agricultural sector.

The coefficient estimate for the patent variable in the TFP equation was negative and insignificant. Therefore, the rates of return to public and private R&D can not be calculated from the system of equations. Therefore, the reduced form for the TFP equation was estimated separately to be able to calculate rates of return.

These rates of return are key in terms of evaluating whether it is feasible to undertake R&D activities for a society. The calculated rate of return to public R&D was -7 percent, the calculated rate of return to private R&D ranged from 50 to 1696 percent,

and the rate of return to extension ranged between 105 and 128 percent.

This study has provided 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, both theoretically and empirically. This study has attempted to conduct a comprehensive analysis of technical change by not only attempting to measure technical change using patent data but also by trying to explain the sources of technical change. In other words, it has tried to answer two questions at the same time: 'What happens?' and 'Why does it happen?'

Doing so required analysis of both the inputs and the outputs of the processes that lead to technical change. It also requires an understanding of the determination of the allocation of resources to activities that result in technical change. The techniques employed in this study and the results generated by them may provide a useful framework for future research that explores the strategies that may be employed to understand how a society may achieve and maintain higher levels of welfare for its citizens.

REFERENCES

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

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.

Cline P. (1975). 'Sources of Productivity Change in U.S. Agriculture' Unpublished Ph.D. Thesis. Stillwater: Oklahoma State University.

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.

Davis, J. (1981). 'A Comparison of Procedures for estimating Returns to Research Using Production Functions', Australian Journal of Agricultural Economics, vol.25, pp. 60-72.

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. (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, 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.

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.

Hallam, D. (1990). 'Agricultural Research Expenditures and Agricultural Productivity Change', Journal of Agricultural Economics, vol. 41, pp. 434-439.

Hamilton, J. D. (1994). 'Time Series Analysis' Princeton, NJ: Princeton University Press.

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.

Just, R. E. (1993). 'Discovering Production and Supply Relationships: Present Status and Future Opportunities', Review of Marketing and Agricultural Economics, vol.61, No.1, pp. 11-40.

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.

Lutkepohl, H. (1991). 'Introduction to Multiple Time Series Analysis', Heidelberg: Weihart-Druck .

Malkeil, B.G (1990). 'A Random Walk Down the Wall Street', 5th edition, New York, Norton Press.

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. no.2, pp. 371-388.

Pardey, P. and B. J. Craig (1989). 'Causal Relationships Between Public Sector Agricultural Research Expenditures and Output', American Journal of Agricultural Economics, vol.71, pp. 9-19.

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.

Roe, T. and H. Mohtadi (1999). 'International Trade and Growth: An Overview from the Perspective of New Growth Theory', AAEA Annual Conference Workshop on Introductions to the New Growth Theory.

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.

Rosegrant, M. W. and R. E. Evenson (1992). 'Agricultural Productivity and Sources of Growth in South Asia', American Journal of Agricultural Economics, vol.74, no.3, pp. 757-761.

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.

Schmookler, J. (1966). 'Invention and Economic Growth', Cambridge, MA: Harvard University Press.

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.

Sumner, D.A. (1995). 'Agricultural Policy Reform in the United States', The AEI Press, Washington, D.C.

Yee J. (1992). ‘Assessing Rates of Return to Public and Private Agricultural Research’, Journal of Agricultural Economics Research, vol.44, no.1, pp.35-41.

APPENDIX A

Table A. 1. Time Series Analysis: Total Factor Productivity (Level)

Augmented Dickey-Fuller Unit Root Tests

Type	Lags	Rho	Pr < Rho	Tau	Pr < Tau	F	Pr > F
Zero Mean	0	0.1849	0.7192	2.39	0.9950		
	1	0.1757	0.7167	4.18	0.9999		
	2	0.1724	0.7157	4.61	0.9999		
	3	0.1662	0.7140	4.95	0.9999		
	4	0.1616	0.7127	5.00	0.9999		
	5	0.1559	0.7110	3.28	0.9995		
	6	0.1523	0.7099	2.33	0.9938		
Single Mean	0	-0.7714	0.9006	-0.52	0.8757	3.02	0.3232
	1	0.0216	0.9538	0.03	0.9549	8.51	0.0010
	2	0.2357	0.9634	0.41	0.9804	10.31	0.0010
	3	0.3035	0.9660	0.73	0.9910	11.95	0.0010
	4	0.3754	0.9686	1.24	0.9977	12.56	0.0010
	5	0.4100	0.9697	1.23	0.9976	5.62	0.0297
	6	0.3558	0.9675	0.85	0.9932	2.76	0.3879
Trend	0	-33.9681	0.0002	-5.38	0.0005	14.48	0.0010
	1	-20.1940	0.0301	-2.98	0.1532	4.52	0.3059
	2	-13.8033	0.1643	-2.14	0.5066	2.53	0.6810
	3	-6.8915	0.6341	-1.47	0.8193	1.51	0.8740
	4	-2.7367	0.9402	-0.86	0.9483	1.29	0.9160
	5	-3.7569	0.8885	-0.99	0.9320	1.41	0.8916
	6	-7.5295	0.5715	-1.17	0.8994	1.19	0.9342

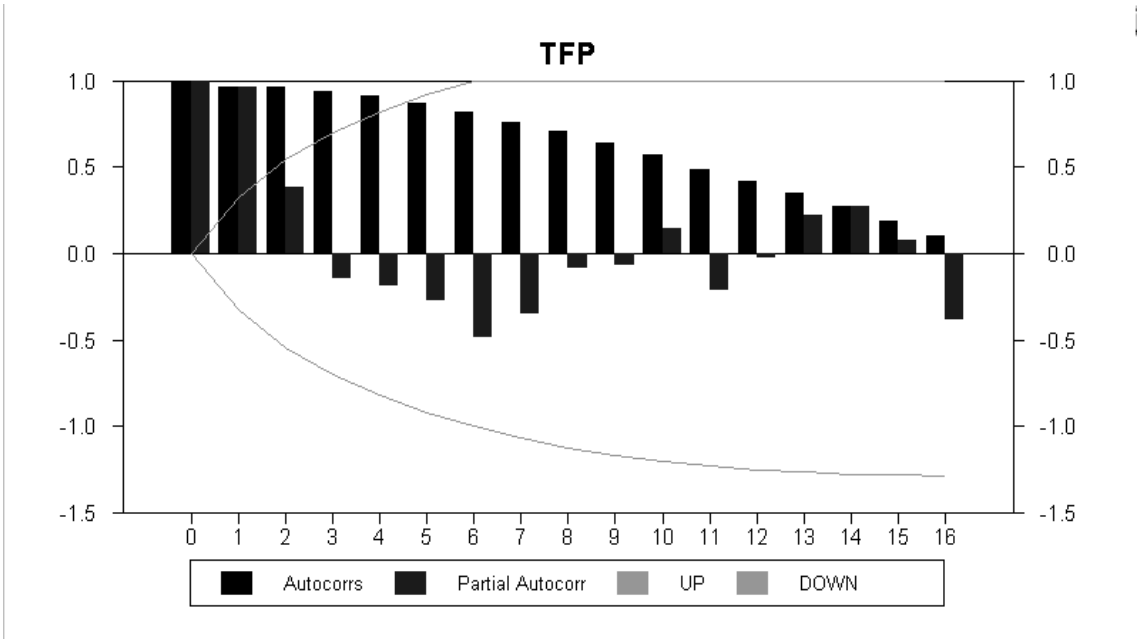

Figure A. 1. Auto-correlation and Partial Auto-correlation Functions

Table A. 2. Time Series Analysis: Public R&D Spending (Level)

Augmented Dickey-Fuller Unit Root Tests

Type	Lags	Rho	Pr < Rho	Tau	Pr < Tau	F	Pr > F
Zero Mean	0	0.0463	0.6872	3.40	0.9997		
	1	0.0417	0.6859	1.83	0.9818		
	2	0.0414	0.6857	1.76	0.9787		
	3	0.0390	0.6849	1.38	0.9548		
	4	0.0336	0.6835	1.33	0.9508		
	5	0.0297	0.6823	1.10	0.9253		
	6	0.0273	0.6816	0.96	0.9069		
Single Mean	0	-2.0191	0.7668	-2.58	0.1059	10.27	0.0010
	1	-2.3103	0.7298	-2.15	0.2266	4.26	0.0828
	2	-2.3914	0.7191	-2.38	0.1541	4.70	0.0585
	3	-2.6016	0.6916	-2.41	0.1453	4.09	0.0917
	4	-1.8834	0.7822	-1.83	0.3581	2.70	0.4028
	5	-1.6770	0.8066	-1.56	0.4893	1.89	0.5994
	6	-1.5493	0.8211	-1.41	0.5642	1.51	0.6937
Trend	0	-1.3718	0.9796	-0.50	0.9790	3.27	0.5420
	1	-3.5239	0.9034	-0.93	0.9418	2.30	0.7245
	2	-3.1213	0.9238	-0.86	0.9491	2.76	0.6373
	3	-4.2500	0.8573	-1.02	0.9270	2.89	0.6139
	4	-1.2520	0.9812	-0.36	0.9846	1.63	0.8502
	5	-0.6751	0.9889	-0.20	0.9902	1.21	0.9315
	6	-0.2181	0.9928	-0.06	0.9932	1.01	0.9638

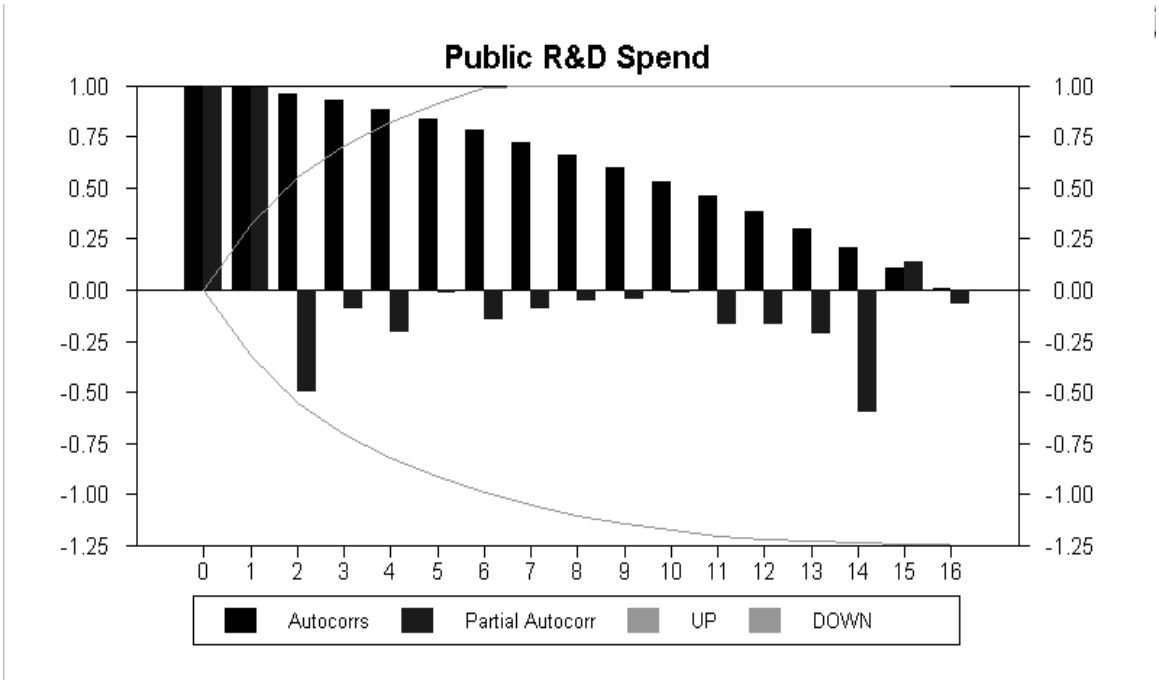

Figure A. 2. Auto-correlation and Partial Auto-correlation Functions

Table A. 3. Time Series Analysis : Private R&D Spending (Level)

Augmented Dickey-Fuller Unit Root Tests

Type	Lags	Rho	Pr < Rho	Tau	Pr < Tau	F	Pr > F
Zero Mean	0	0.0716	0.6929	3.73	0.9999		
	1	0.0715	0.6927	3.49	0.9997		
	2	0.0687	0.6918	2.74	0.9979		
	3	0.0672	0.6912	2.54	0.9965		
	4	0.0626	0.6900	1.98	0.9868		
	5	0.0555	0.6881	1.97	0.9861		
	6	0.0511	0.6869	1.38	0.9550		
Single Mean	0	-1.0233	0.8779	-1.25	0.6402	8.03	0.0010
	1	-1.1214	0.8682	-1.53	0.5058	7.73	0.0010
	2	-1.1447	0.8656	-1.49	0.5283	5.18	0.0416
	3	-1.1940	0.8604	-1.64	0.4504	4.94	0.0478
	4	-1.1141	0.8682	-1.38	0.5773	3.11	0.3033
	5	-0.5746	0.9155	-0.77	0.8150	2.26	0.5109
	6	-0.6373	0.9104	-0.69	0.8332	1.22	0.7640
Trend	0	-6.7250	0.6525	-1.66	0.7489	1.84	0.8115
	1	-6.0350	0.7138	-1.48	0.8174	1.92	0.7969
	2	-7.8348	0.5504	-1.55	0.7909	1.97	0.7875
	3	-7.8163	0.5506	-1.44	0.8285	2.04	0.7730
	4	-12.8562	0.2009	-1.52	0.8009	1.82	0.8143
	5	-11.3555	0.2786	-1.26	0.8801	0.95	0.9722
	6	80.8900	0.9999	-1.74	0.7073	1.62	0.8524

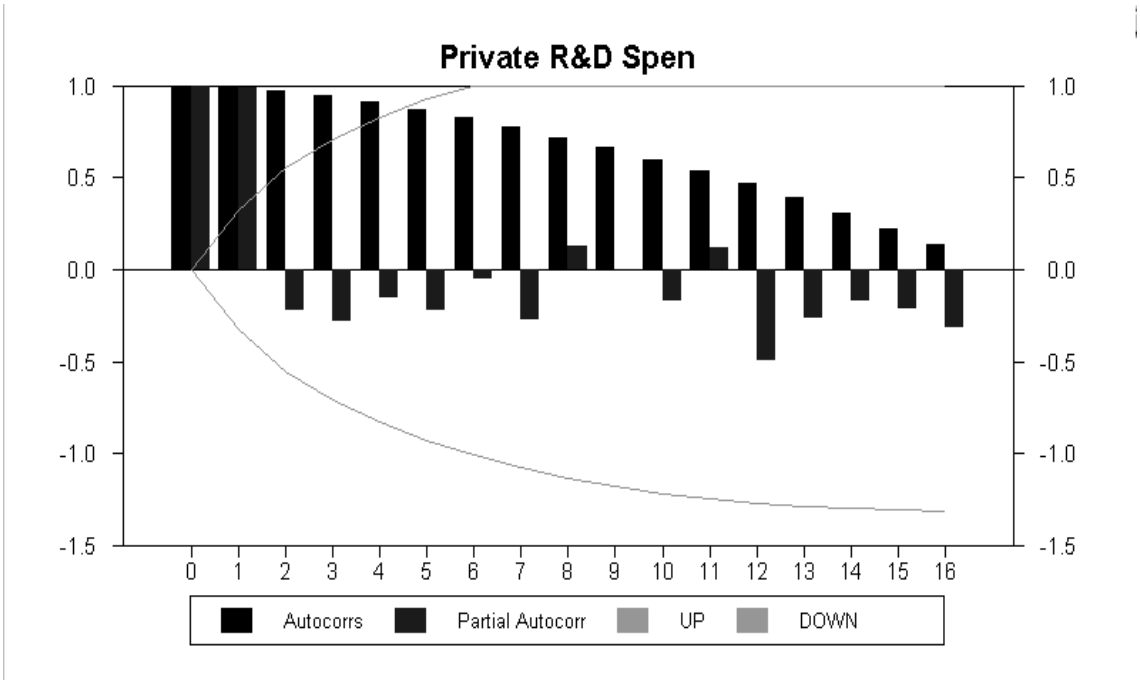

Figure A. 3. Auto-correlation and Partial Auto-correlation Functions

Table A. 4. Time Series Analysis: Extension Spending (Level)

Augmented Dickey-Fuller Unit Root Tests

Type	Lags	Rho	Pr < Rho	Tau	Pr < Tau	F	Pr > F
Zero Mean	0	0.1954	0.7217	3.99	0.9999		
	1	0.1917	0.7206	4.62	0.9999		
	2	0.1873	0.7193	4.04	0.9999		
	3	0.1823	0.7178	3.15	0.9993		
	4	0.1776	0.7164	2.59	0.9968		
	5	0.1727	0.7150	2.15	0.9908		
	6	0.1667	0.7133	1.67	0.9739		
Single Mean	0	-0.6292	0.9122	-0.83	0.7982	8.58	0.0010
	1	-0.4977	0.9220	-0.93	0.7662	11.72	0.0010
	2	-0.4811	0.9230	-1.05	0.7239	9.52	0.0010
	3	-0.5123	0.9205	-1.14	0.6871	6.35	0.0145
	4	-0.5478	0.9177	-1.26	0.6371	4.90	0.0489
	5	-0.5830	0.9148	-1.37	0.5831	4.01	0.0964
	6	-0.6487	0.9095	-1.47	0.5341	3.13	0.2971
Trend	0	-16.1568	0.0940	-2.80	0.2063	4.08	0.3878
	1	-9.8813	0.3848	-1.70	0.7301	1.75	0.8278
	2	-7.3898	0.5901	-1.22	0.8904	1.19	0.9347
	3	-8.0825	0.5272	-1.08	0.9168	1.14	0.9436
	4	-8.0537	0.5281	-0.91	0.9425	1.11	0.9492
Trend	5	-7.2409	0.5994	-0.73	0.9612	1.12	0.9476
	6	-9.8036	0.3805	-0.70	0.9639	1.24	0.9258

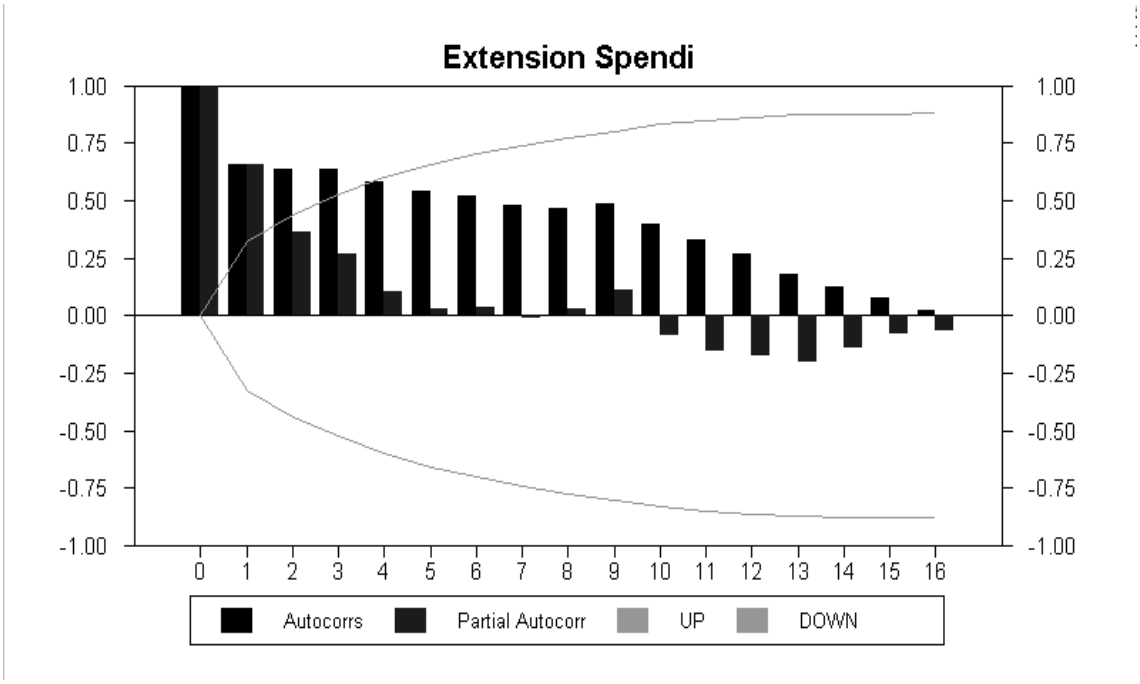

Figure A. 4. Auto-correlation and Partial Auto-correlation Functions

Table A. 5. Time Series Analysis: Patents (Level)

		Augmented Dickey-Fuller Unit Root Tests					
Type	Lags	Rho	Pr < Rho	Tau	Pr < Tau	F	Pr > F
Zero Mean	0	0.0521	0.6885	0.28	0.7602		
	1	0.0191	0.6809	0.11	0.7110		
	2	0.0143	0.6796	0.09	0.7064		
	3	0.0263	0.6821	0.22	0.7425		
	4	0.0331	0.6833	0.35	0.7800		
	5	0.0369	0.6840	0.51	0.8205		
	6	-0.0247	0.6700	-0.21	0.6013		
Single Mean	0	-12.8118	0.0477	-3.25	0.0249	5.37	0.0363
	1	-13.2896	0.0408	-2.77	0.0719	3.87	0.1161
	2	-13.1351	0.0423	-2.49	0.1268	3.11	0.3018
	3	-12.6735	0.0480	-2.41	0.1457	2.96	0.3393
	4	-10.9485	0.0796	-2.37	0.1576	2.91	0.3518
	5	-10.4859	0.0904	-2.66	0.0924	3.74	0.1495
	6	-26.7674	0.0002	-2.20	0.2108	2.43	0.4673
Trend	0	-12.0691	0.2480	-3.00	0.1453	5.75	0.0937
	1	-12.2338	0.2375	-2.62	0.2732	4.26	0.3548
	2	-11.6202	0.2693	-2.39	0.3792	3.72	0.4572
	3	-10.5063	0.3370	-2.41	0.3685	4.40	0.3283
	4	-8.6901	0.4734	-2.72	0.2347	6.82	0.0480
	5	-7.9403	0.5364	-6.13	0.0001	38.35	0.0010
	6	-9.2310	0.4249	-4.08	0.0166	8.34	0.0166

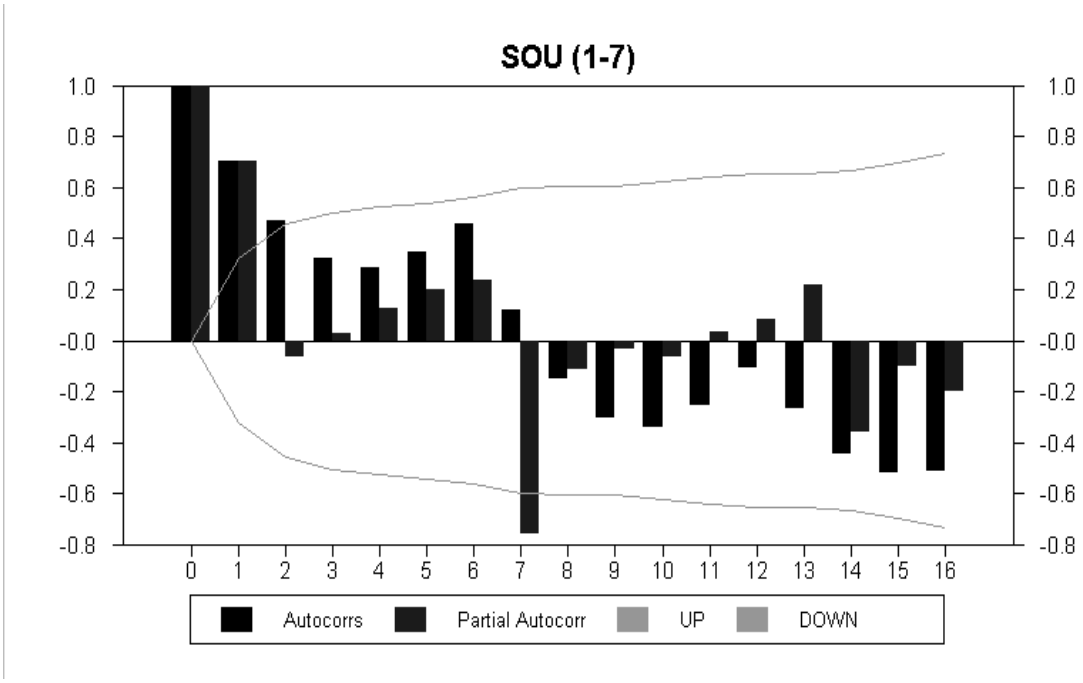

Figure A. 5. Auto-correlation and Partial Auto-correlation Functions

Table A. 6. Time Series Analysis: Real Interest Rate (Level)

Augmented Dickey-Fuller Unit Root Tests

Type	Lags	Rho	Pr < Rho	Tau	Pr < Tau	F	Pr > F
Zero Mean	0	-6.8651	0.0635	-1.92	0.0527		
	1	-14.7174	0.0046	-2.59	0.0111		
	2	-6.0017	0.0837	-1.57	0.1084		
	3	-9.8462	0.0233	-1.79	0.0705		
	4	-4.7780	0.1245	-1.27	0.1824		
	5	-7.4172	0.0519	-1.37	0.1556		
	6	-12.6941	0.0086	-1.53	0.1150		
Single Mean	0	-9.2387	0.1342	-2.24	0.1966	2.51	0.4496
	1	-22.6009	0.0017	-3.20	0.0283	5.12	0.0432
	2	-9.8521	0.1114	-1.94	0.3114	1.88	0.6021
	3	-20.7016	0.0033	-2.30	0.1771	2.65	0.4136
	4	-9.5223	0.1207	-1.63	0.4566	1.33	0.7370
	5	-23.1276	0.0012	-1.88	0.3370	1.78	0.6267
	6	-174.597	0.0001	-2.03	0.2748	2.05	0.5601
Trend	0	-10.1175	0.3692	-2.39	0.3782	2.95	0.6021
	1	-24.5979	0.0075	-3.34	0.0757	5.61	0.1001
	2	-11.7707	0.2607	-2.14	0.5038	2.37	0.7111
	3	-28.4159	0.0016	-2.58	0.2895	3.39	0.5184
	4	-14.8170	0.1247	-1.97	0.5954	2.03	0.7761
	5	-51.8678	<.0001	-2.18	0.4831	2.39	0.7078
	6	48.2304	0.9999	-2.63	0.2726	3.53	0.4921

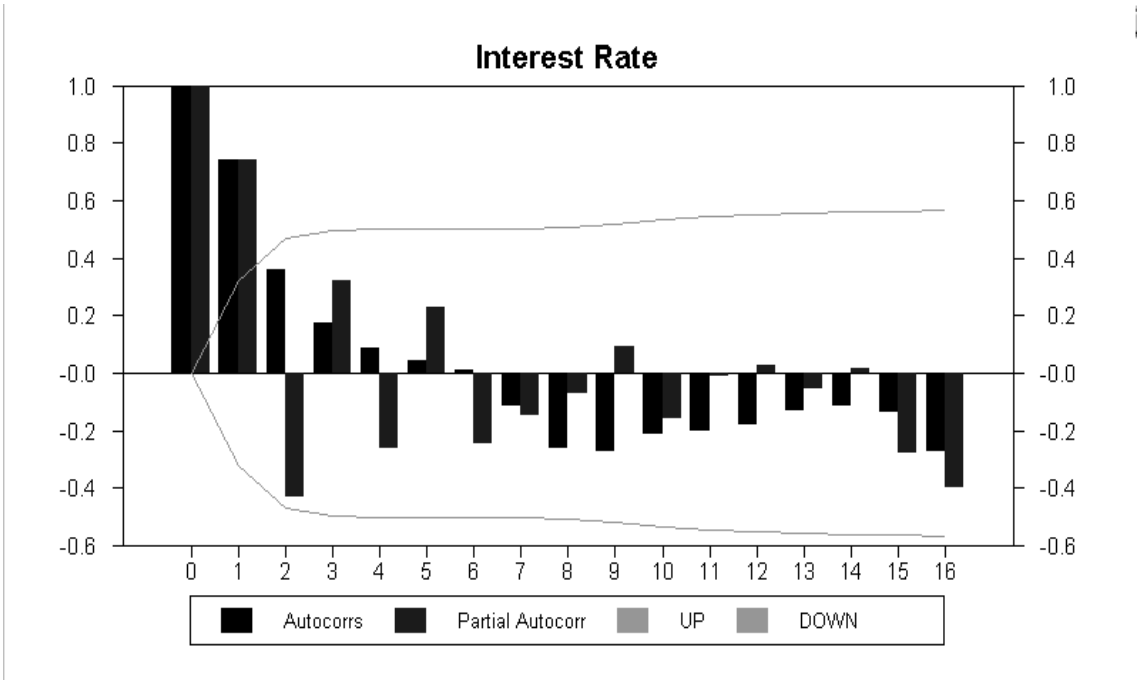

Figure A. 6. Auto-correlation and Partial Auto-correlation Functions

Table A. 7. Time Series Analysis: Quality Index (Level)

Augmented Dickey-Fuller Unit Root Tests

Type	Lags	Rho	Pr < Rho	Tau	Pr < Tau	F	Pr > F
Zero Mean	0	0.1336	0.7071	5.35	0.9999		
	1	0.0315	0.6836	0.19	0.7364		
	2	0.0619	0.6903	0.53	0.8251		
	3	0.0363	0.6843	0.23	0.7472		
	4	-0.0706	0.6603	-0.27	0.5797		
	5	-0.4005	0.5857	-0.69	0.4077		
	6	-0.4569	0.5729	-1.31	0.1715		
Single Mean	0	-2.5518	0.6992	-8.04	0.0002	79.22	0.0010
	1	-2.9965	0.6416	-2.77	0.0729	3.88	0.1146
	2	-2.8130	0.6648	-2.92	0.0535	4.49	0.0700
	3	-3.1425	0.6220	-3.30	0.0225	5.52	0.0324
	4	-3.5345	0.5722	-3.60	0.0109	6.52	0.0112
	5	-4.0134	0.5139	-6.15	0.0002	19.38	0.0010
	6	-4.2866	0.4817	-9.10	0.0002	44.95	0.0010
Trend	0	-0.4513	0.9915	-0.69	0.9663	49.57	0.0010
	1	-1.7941	0.9707	-1.32	0.8656	4.05	0.3939
	2	-0.8609	0.9871	-0.91	0.9439	5.93	0.0857
	3	-1.0837	0.9840	-1.36	0.8532	7.53	0.0316
	4	-1.6180	0.9743	-2.14	0.5061	7.91	0.0234
	5	-2.2637	0.9570	-4.82	0.0027	22.89	0.0010
	6	-3.0292	0.9270	-9.67	0.0001	52.94	0.0010

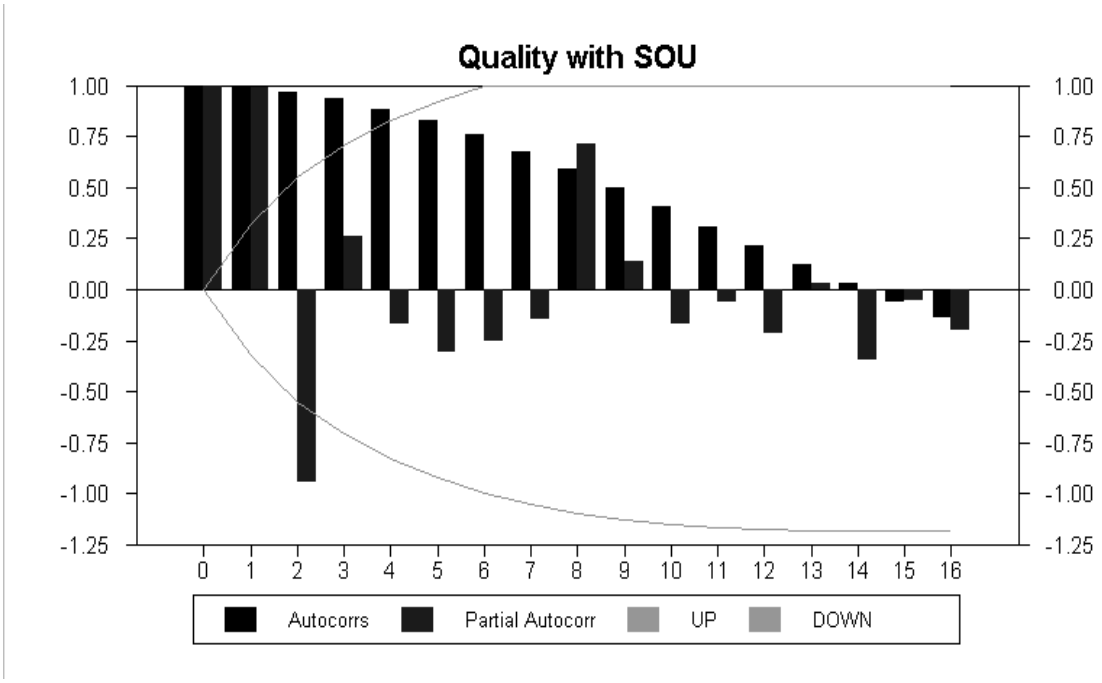

Figure A. 7. Auto-correlation and Partial Auto-correlation Functions

Table A. 8. Time Series Analysis: Price of Agriculture Output (Level)

Augmented Dickey-Fuller Unit Root Tests

Type	Lags	Rho	Pr < Rho	Tau	Pr < Tau	F	Pr > F
Zero Mean	0	-0.0880	0.6572	-0.95	0.2998		
	1	-0.0846	0.6578	-0.72	0.3999		
	2	-0.0876	0.6569	-1.05	0.2594		
	3	-0.0844	0.6575	-1.03	0.2677		
	4	-0.0798	0.6583	-1.10	0.2417		
	5	-0.0824	0.6575	-0.90	0.3191		
	6	-0.0851	0.6567	-1.10	0.2382		
Single Mean	0	-2.0855	0.7585	-0.88	0.7839	0.80	0.8665
	1	-4.3701	0.4763	-1.31	0.6154	1.08	0.7976
	2	-1.6716	0.8081	-0.68	0.8385	0.75	0.8790
	3	-1.5113	0.8263	-0.59	0.8593	0.67	0.8978
	4	-0.6142	0.9126	-0.27	0.9186	0.61	0.9169
	5	-2.5442	0.6981	-0.68	0.8363	0.61	0.9160
	6	-1.3233	0.8461	-0.45	0.8874	0.67	0.8967
Trend	0	-6.7635	0.6491	-1.91	0.6306	1.92	0.7964
	1	-12.8350	0.2078	-2.44	0.3528	3.02	0.5884
	2	-7.2230	0.6052	-1.74	0.7137	1.64	0.8484
	3	-7.7062	0.5604	-1.69	0.7328	1.62	0.8530
	4	-6.1774	0.6982	-1.52	0.7998	1.59	0.8584
	5	-13.3759	0.1757	-1.77	0.6972	1.74	0.8298
	6	-8.1155	0.5191	-1.40	0.8406	1.16	0.9406

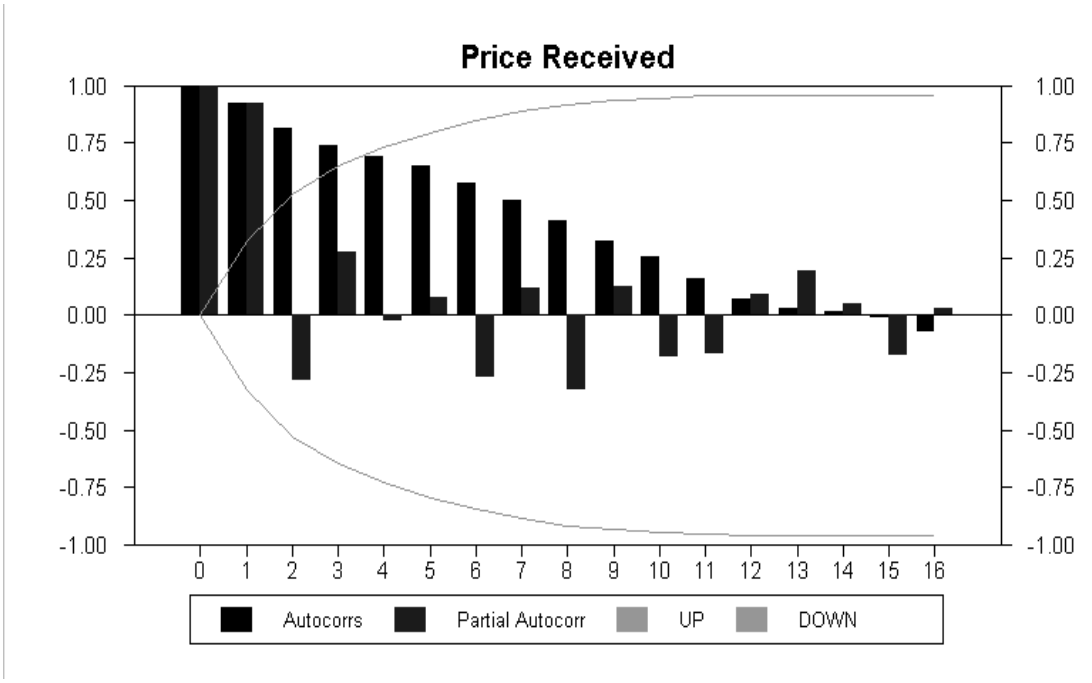

Figure A. 8. Auto-correlation and Partial Auto-correlation Functions

Table A. 9. Time Series Analysis: Public R&D Spending (1st differenced)

Augmented Dickey-Fuller Unit Root Tests

Type	Lags	Rho	Pr < Rho	Tau	Pr < Tau	F	Pr > F
Zero Mean	0	-17.9320	0.0015	-3.42	0.0012		
	1	-15.1281	0.0040	-2.65	0.0094		
	2	-9.6538	0.0249	-1.97	0.0477		
	3	-11.2866	0.0143	-2.21	0.0283		
	4	-8.6131	0.0348	-2.00	0.0446		
	5	-7.1435	0.0565	-1.83	0.0647		
	6	-4.5859	0.1321	-1.29	0.1765		
Single Mean	0	-24.0682	0.0010	-3.99	0.0038	8.02	0.0010
	1	-26.7012	0.0003	-3.27	0.0243	5.39	0.0359
	2	-20.6720	0.0033	-2.43	0.1420	3.02	0.3248
	3	-31.8270	0.0002	-2.50	0.1236	3.44	0.2216
	4	-26.0575	0.0004	-2.12	0.2372	2.66	0.4119
	5	-24.3280	0.0007	-1.87	0.3437	2.16	0.5341
	6	-16.9890	0.0112	-1.39	0.5746	1.15	0.7804
Trend	0	-28.2255	0.0020	-4.57	0.0045	10.50	0.0010
	1	-38.4460	<.0001	-4.06	0.0160	8.40	0.0156
	2	-42.8000	<.0001	-3.32	0.0813	5.68	0.0968
	3	-118.027	0.0001	-3.17	0.1090	5.02	0.2118
	4	-206.299	0.0001	-2.69	0.2463	3.63	0.4744
	5	341.6555	0.9999	-2.40	0.3718	2.88	0.6149
	6	50.8989	0.9999	-2.22	0.4596	2.62	0.6649

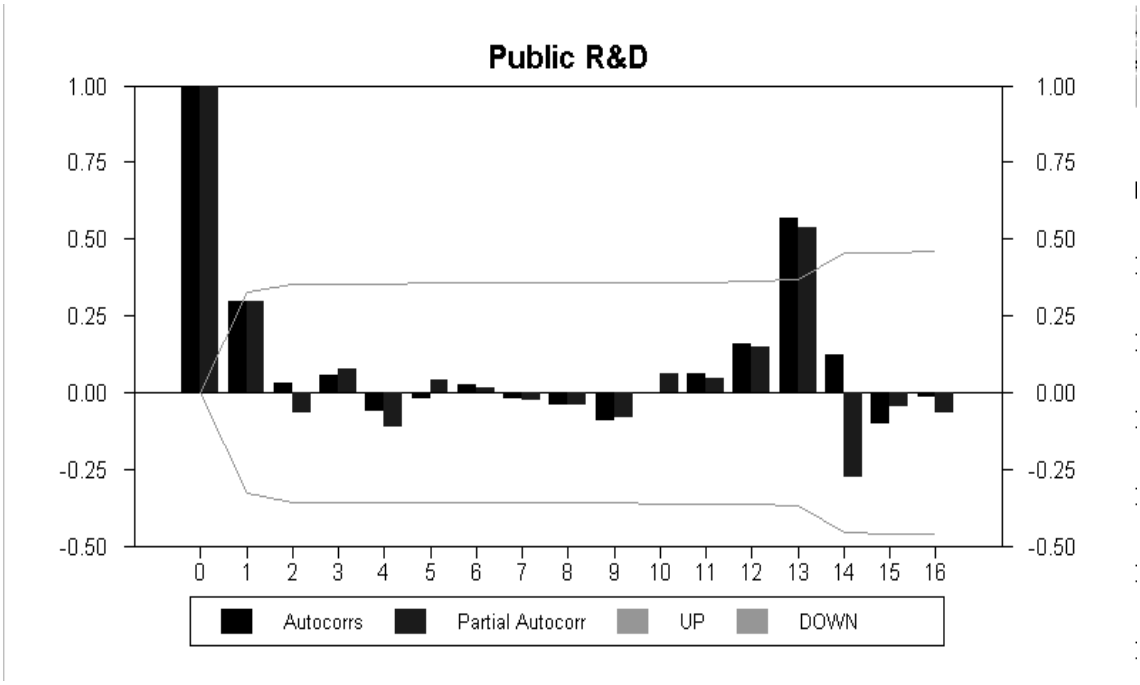

Figure A. 9. Auto-correlation and Partial Auto-correlation Functions

Table A. 10. Time Series Analysis: Private R&D Spending (1st differenced)

Augmented Dickey-Fuller Unit Root Tests

Type	Lags	Rho	Pr < Rho	Tau	Pr < Tau	F	Pr > F
Zero Mean	0	-27.6197	<.0001	-4.71	<.0001		
	1	-15.1252	0.0040	-2.68	0.0088		
	2	-10.5118	0.0187	-2.05	0.0404		
	3	-6.2979	0.0755	-1.61	0.0994		
	4	-6.4344	0.0719	-1.90	0.0560		
	5	-3.5251	0.1891	-1.45	0.1347		
	6	-3.3618	0.1990	-1.14	0.2243		
Single Mean	0	-39.4756	0.0002	-6.50	0.0002	21.14	0.0010
	1	-36.5969	0.0002	-4.07	0.0031	8.29	0.0010
	2	-46.1332	0.0002	-3.43	0.0164	5.90	0.0232
	3	-34.8139	0.0002	-2.64	0.0945	3.52	0.2019
	4	-53.3456	0.0002	-2.75	0.0764	4.00	0.0966
	5	-19.6284	0.0043	-1.95	0.3055	2.09	0.5517
	6	-177.586	0.0001	-2.02	0.2790	2.07	0.5558
Trend	0	-40.4332	<.0001	-6.67	0.0001	22.31	0.0010
	1	-40.9864	<.0001	-4.27	0.0096	9.13	0.0038
	2	-62.9693	<.0001	-3.75	0.0330	7.05	0.0426
	3	-55.9763	<.0001	-2.89	0.1796	4.17	0.3720
	4	-82.3527	<.0001	-2.71	0.2392	3.85	0.4329
	5	-25.2888	0.0042	-1.94	0.6091	1.93	0.7935
	6	93.3953	0.9999	-2.18	0.4825	2.38	0.7097

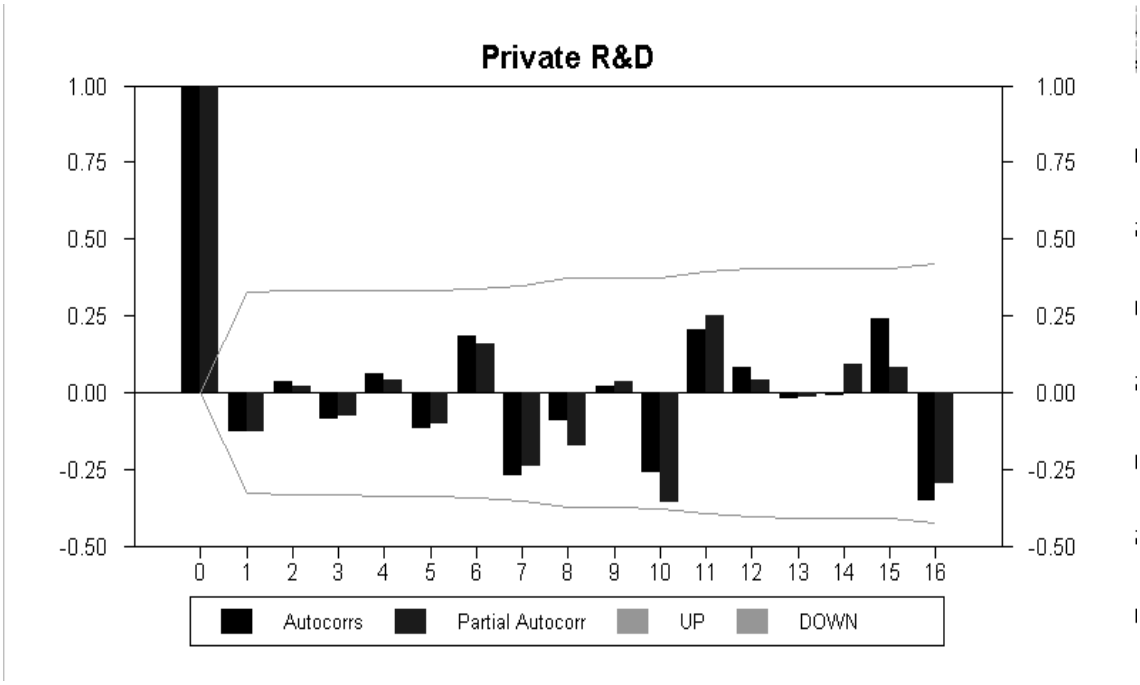

Figure A. 10. Auto-correlation and Partial Auto-correlation Functions

Table A. 11. Time Series Analysis: Extension Funds (1st differenced)

Augmented Dickey-Fuller Unit Root Tests

Type	Lags	Rho	Pr < Rho	Tau	Pr < Tau	F	Pr > F
Zero Mean	0	-51.6002	<.0001	-9.77	<.0001		
	1	-97.6288	<.0001	-6.79	<.0001		
	2	-240.687	0.0001	-4.87	<.0001		
	3	12050.26	0.9999	-3.76	0.0005		
	4	159.1031	0.9999	-3.17	0.0025		
	5	113.2968	0.9999	-2.65	0.0098		
	6	55.4258	0.9999	-2.38	0.0190		
Single Mean	0	-51.9287	0.0002	-9.73	0.0002	47.38	0.0010
	1	-103.487	0.0001	-6.86	0.0002	23.55	0.0010
	2	-445.742	0.0001	-5.01	0.0003	12.58	0.0010
	3	208.9864	0.9999	-3.96	0.0044	7.86	0.0010
	4	65.0769	0.9999	-3.43	0.0169	5.91	0.0229
	5	40.1139	0.9999	-2.95	0.0507	4.38	0.0759
	6	23.6134	0.9999	-2.77	0.0740	3.87	0.1168
Trend	0	-52.0989	<.0001	-9.65	0.0001	46.55	0.0010
	1	-106.569	0.0001	-6.86	0.0001	23.50	0.0010
	2	-727.508	0.0001	-5.07	0.0013	12.83	0.0010
	3	150.8856	0.9999	-4.06	0.0167	8.24	0.0181
	4	54.7532	0.9999	-3.57	0.0492	6.40	0.0649
	5	33.7468	0.9999	-3.13	0.1171	4.94	0.2265
	6	20.5340	0.9999	-3.03	0.1424	4.63	0.2854

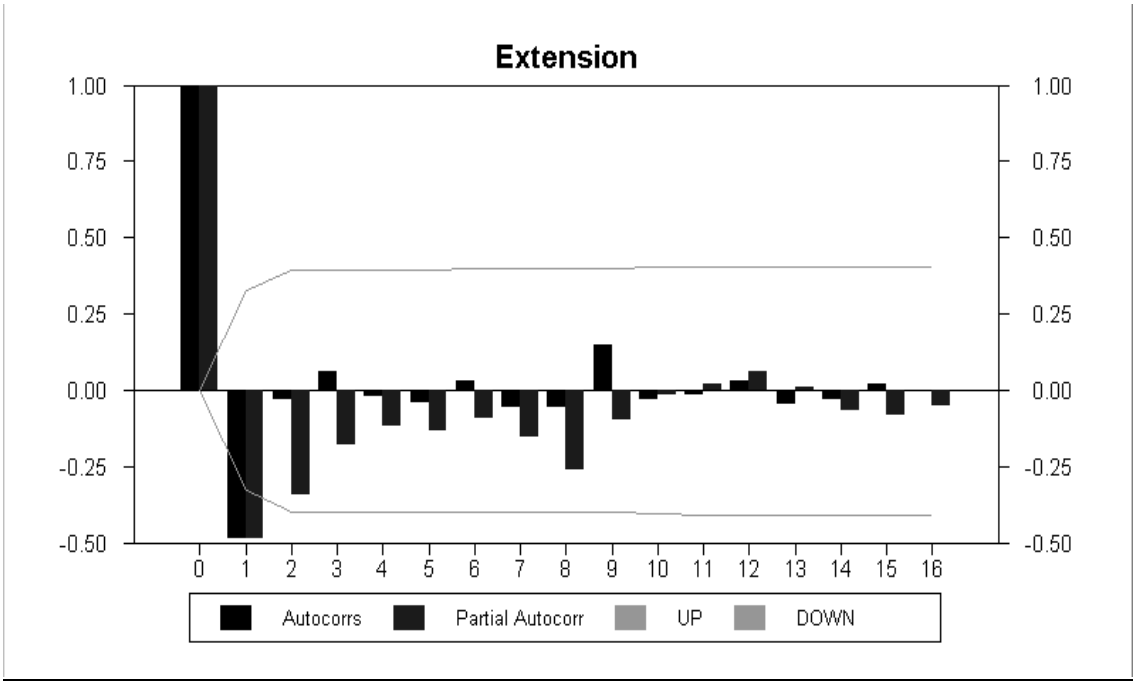

Figure A. 11. Auto-correlation and Partial Auto-correlation Functions

Table A. 12. Time Series Analysis: TFP (1st differenced)

Augmented Dickey-Fuller Unit Root Tests

Type	Lags	Rho	Pr < Rho	Tau	Pr < Tau	F	Pr > F
Zero Mean	0	-48.4890	<.0001	-8.72	<.0001		
	1	-35.8916	<.0001	-4.14	0.0001		
	2	-20.3014	0.0006	-2.65	0.0096		
	3	-8.9909	0.0308	-1.76	0.0737		
	4	-2.3019	0.2916	-0.94	0.2993		
	5	-0.7780	0.5062	-0.51	0.4872		
	6	-0.5040	0.5594	-0.38	0.5365		
Single Mean	0	-55.9567	0.0002	-11.42	0.0002	65.26	0.0010
	1	-110.782	0.0001	-6.99	0.0002	24.46	0.0010
	2	290.0992	0.9999	-6.01	0.0002	18.05	0.0010
	3	58.3953	0.9999	-5.35	0.0002	14.33	0.0010
	4	87.8163	0.9999	-3.28	0.0245	5.36	0.0366
	5	-124.593	0.0001	-2.27	0.1877	2.58	0.4318
	6	-141.591	0.0001	-1.98	0.2948	1.96	0.5824
Trend	0	-55.9637	<.0001	-11.28	0.0001	63.66	0.0010
	1	-114.188	0.0001	-6.96	0.0001	24.22	0.0010
	2	252.0107	0.9999	-6.06	0.0001	18.35	0.0010
	3	52.6814	0.9999	-5.60	0.0004	15.70	0.0010
	4	53.2565	0.9999	-3.60	0.0464	6.48	0.0612
	5	108.5196	0.9999	-2.48	0.3364	3.08	0.5774
	6	52.9870	0.9999	-2.21	0.4658	2.46	0.6946

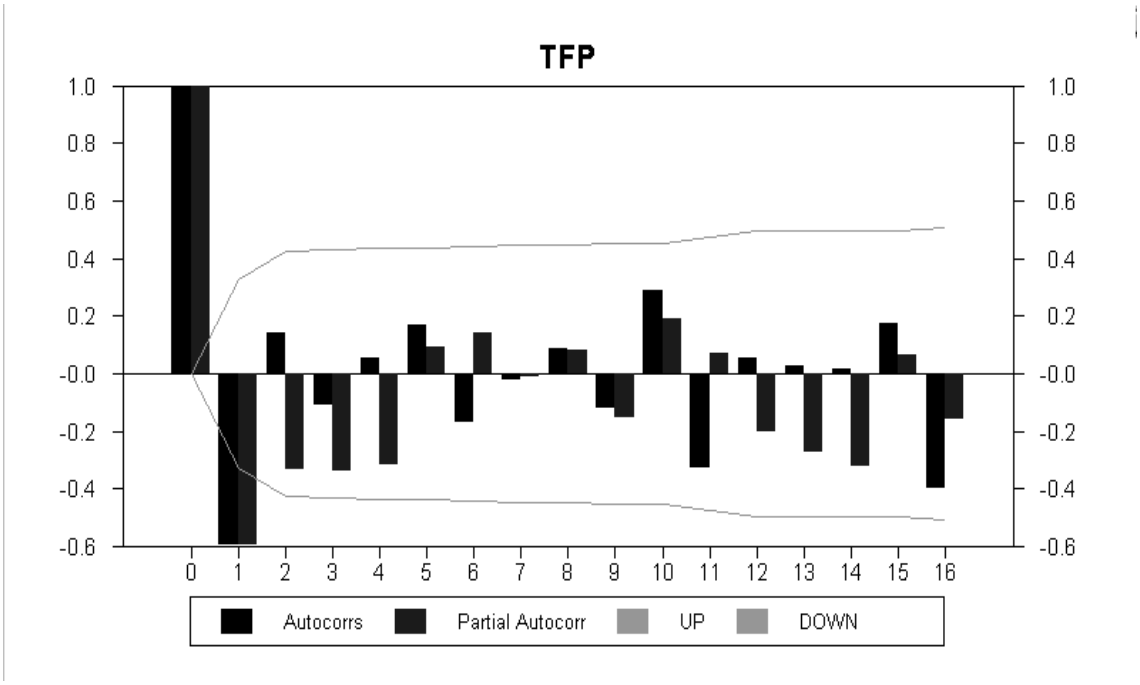

Figure A. 12. Auto-correlation and Partial Auto-correlation Functions

Table A. 13. Time Series Analysis: Real Interest Rate (1st differenced)

		Augmented Dickey-Fuller Unit Root Tests					
Type	Lags	Rho	Pr < Rho	Tau	Pr < Tau	F	Pr > F
Zero Mean	0	-26.0759	<.0001	-4.52	<.0001		
	1	-73.1074	<.0001	-5.88	<.0001		
	2	-44.3846	<.0001	-3.45	0.0011		
	3	193.6401	0.9999	-4.06	0.0002		
	4	-137.279	0.0001	-2.76	0.0074		
	5	-107.274	0.0001	-2.29	0.0232		
	6	92.3869	0.9999	-2.31	0.0225		
Single Mean	0	-26.0736	0.0005	-4.45	0.0011	9.91	0.0010
	1	-73.0942	0.0002	-5.79	0.0002	16.75	0.0010
	2	-44.3126	0.0002	-3.39	0.0182	5.76	0.0261
	3	194.0955	0.9999	-3.98	0.0041	7.94	0.0010
	4	-135.727	0.0001	-2.70	0.0848	3.67	0.1666
	5	-107.237	0.0001	-2.24	0.1959	2.52	0.4469
	6	92.9558	0.9999	-2.26	0.1920	2.58	0.4313
Trend	0	-26.1340	0.0044	-4.38	0.0071	9.62	0.0010
	1	-73.7599	<.0001	-5.72	0.0003	16.35	0.0010
	2	-44.7821	<.0001	-3.35	0.0762	5.61	0.1000
	3	187.4199	0.9999	-3.93	0.0221	7.76	0.0262
	4	-142.393	0.0001	-2.65	0.2628	3.52	0.4952
	5	-131.390	0.0001	-2.23	0.4589	2.49	0.6887
	6	94.0852	0.9999	-2.18	0.4799	2.43	0.7009

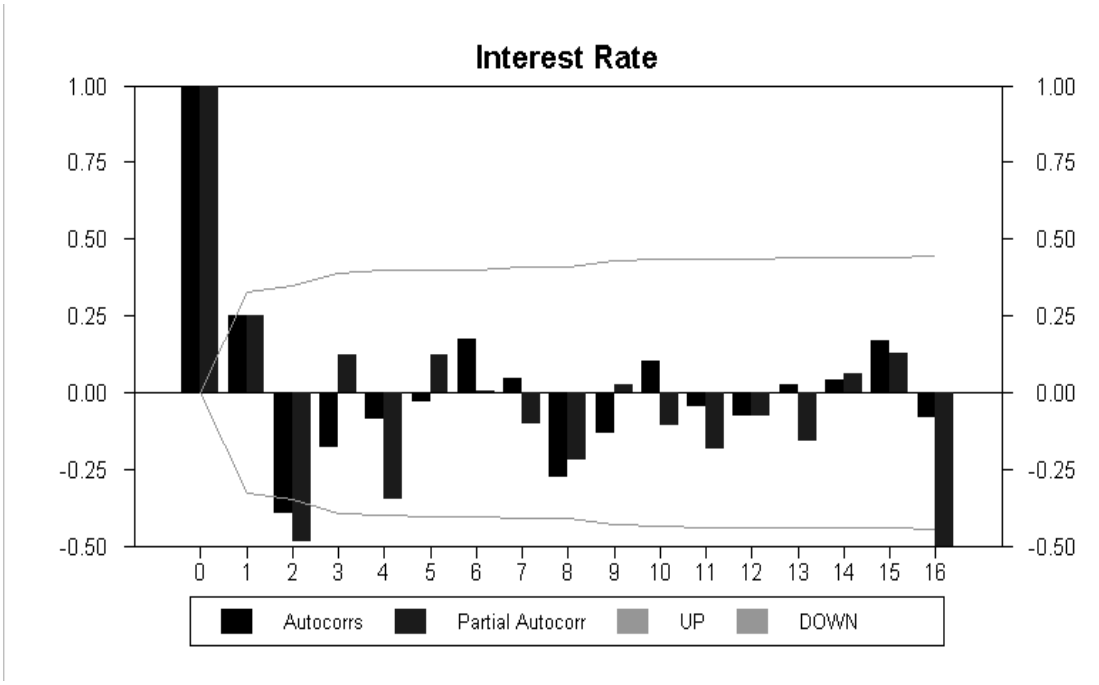

Figure A. 13. Auto-correlation and Partial Auto-correlation Functions

Table A. 14. Time Series Analysis: Price of Agriculture Output (1st diffrenced)

Augmented Dickey-Fuller Unit Root Tests

Type	Lags	Rho	Pr < Rho	Tau	Pr < Tau	F	Pr > F
Zero Mean	0	-27.0579	<.0001	-4.56	<.0001		
	1	-52.8316	<.0001	-4.90	<.0001		
	2	-54.8055	<.0001	-3.65	0.0006		
	3	-121.989	0.0001	-3.31	0.0016		
	4	-23.8668	0.0001	-2.15	0.0325		
	5	-83.2193	<.0001	-2.23	0.0268		
	6	-11.4246	0.0130	-1.51	0.1205		
Single Mean	0	-27.8127	0.0002	-4.56	0.0008	10.43	0.0010
	1	-57.8638	0.0002	-5.01	0.0003	12.55	0.0010
	2	-70.1002	0.0002	-3.78	0.0069	7.16	0.0010
	3	-561.751	0.0001	-3.49	0.0146	6.11	0.0191
	4	-40.5812	0.0002	-2.31	0.1766	2.66	0.4111
	5	160.6010	0.9999	-2.49	0.1276	3.10	0.3049
	6	-18.9451	0.0055	-1.60	0.4708	1.29	0.7453
Trend	0	-28.0448	0.0022	-4.49	0.0054	10.16	0.0010
	1	-60.1054	<.0001	-4.95	0.0017	12.36	0.0010
	2	-80.1267	<.0001	-3.77	0.0315	7.16	0.0400
	3	422.0116	0.9999	-3.58	0.0477	6.45	0.0625
	4	-64.8927	<.0001	-2.31	0.4161	2.75	0.6389
	5	70.1190	0.9999	-2.46	0.3435	3.19	0.5571
	6	-45.5498	<.0001	-1.74	0.7078	1.52	0.8720

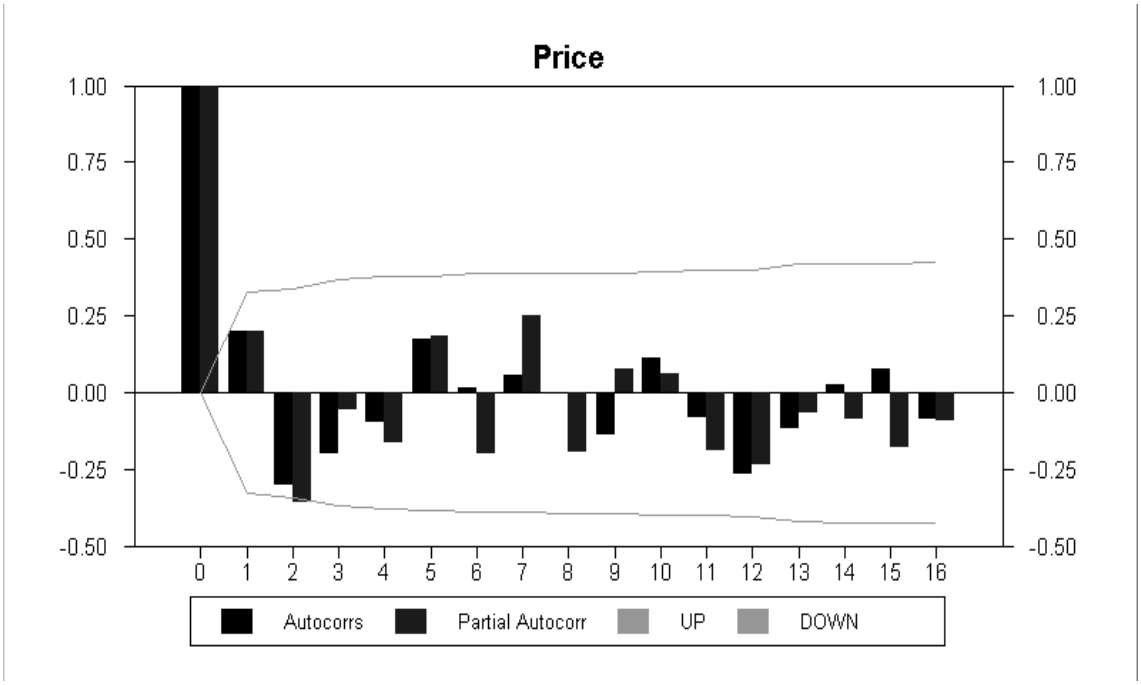

Figure A. 14. Auto-correlation and Partial Auto-correlation Functions

Table A. 15. Time Series Analysis: Quality Stock (1st differenced)

Augmented Dickey-Fuller Unit Root Tests

Type	Lags	Rho	Pr < Rho	Tau	Pr < Tau	F	Pr > F
Zero Mean	0	-2.7699	0.2474	-1.50	0.1236		
	1	-4.0572	0.1588	-1.75	0.0751		
	2	-2.8083	0.2437	-1.40	0.1465		
	3	-1.8270	0.3462	-1.26	0.1862		
	4	-1.3114	0.4164	-1.17	0.2166		
	5	-1.7132	0.3602	-2.06	0.0394		
	6	-3.4854	0.1908	-4.03	0.0002		
Single Mean	0	-3.3176	0.6009	-1.24	0.6462	1.13	0.7853
	1	-5.7660	0.3387	-1.65	0.4460	1.70	0.6458
	2	-3.6216	0.5621	-1.17	0.6734	1.00	0.8163
	3	-1.4861	0.8288	-0.69	0.8354	0.78	0.8698
	4	-0.5061	0.9206	-0.32	0.9107	0.84	0.8552
	5	-0.4786	0.9224	-0.46	0.8861	2.94	0.3449
	6	-2.8546	0.6604	-2.46	0.1354	7.88	0.0010
Trend	0	-13.7032	0.1700	-2.82	0.1986	4.00	0.4043
	1	-33.4747	0.0002	-3.84	0.0266	7.36	0.0354
	2	-66.3495	<.0001	-3.84	0.0271	7.38	0.0350
	3	-72.2118	<.0001	-3.23	0.0970	5.26	0.1657
	4	-232.925	0.0001	-3.38	0.0723	5.91	0.0866
	5	-13.4576	0.1700	-1.61	0.7656	1.30	0.9138
	6	-8.3168	0.4994	-1.11	0.9102	3.11	0.5724

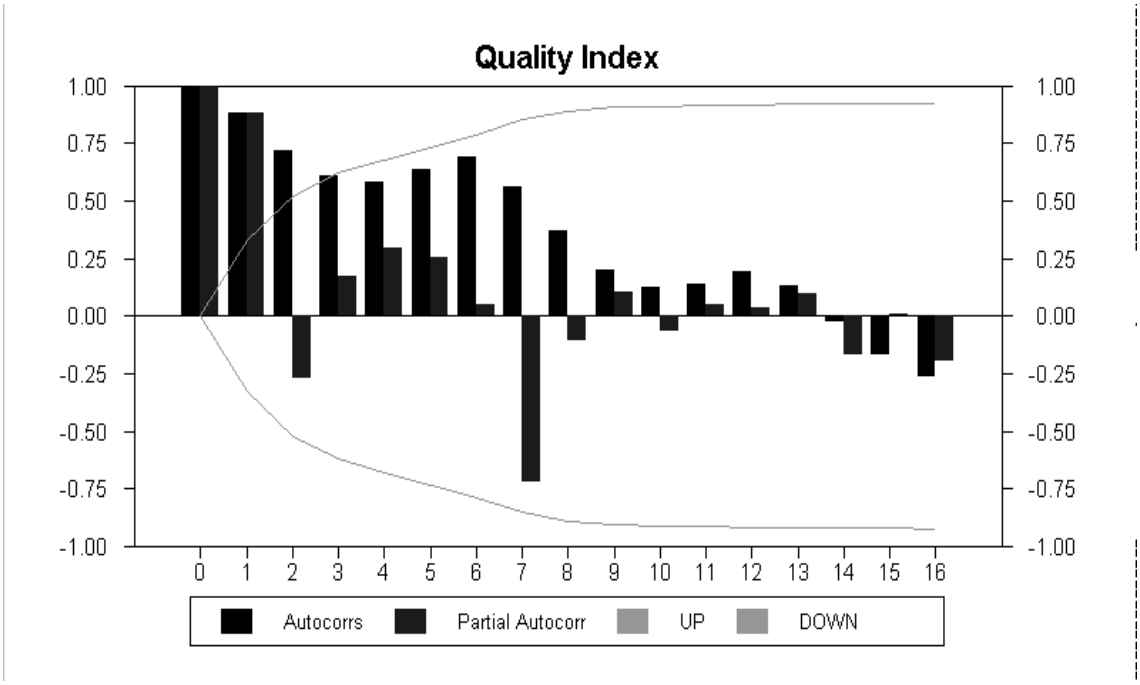

Figure A. 15. Auto-correlation and Partial Auto-correlation Functions

APPENDIX B

The theoretical model discussed in Chapter 3 reveals that private R&D spending and technical change are endogenously determined in the economic system. This concept of "economic endogeneity" is considered in the empirical part of this study when private R&D spending and patent equations were included in the system of equations with total factor productivity, and seemingly unrelated regressions techniques was used as the estimation method. In Appendix B, the concept of "economic endogeneity" is enlarged to include the concept of "statistical endogeneity". To do that, one major departure from the empirical analysis if this study is required –i.e., current lags of public and private R&D variables, total factor productivity are included in the empirical specification. This creates a system of equations where the dependent variables appear as explanatory variables in the equations of the system. The results from this exercise are presented below.

B.1 Choosing the Lag Lengths

Equations 4.9, 4.10 and 4.11 were first estimated separately with ordinary least squares and Likelihood Ratio (LR) tests were used to choose the optimal lag lengths for the explanatory variables.

The results with ordinary least squares (OLS) estimation are shown in Appendix B Table B.1. For the TFP equation, LR tests indicated that two lags for extension funds, zero lags for patent and seven lags for public R&D investment are optimal. So the equation for TFP is written as

$$\Delta \ln TFP_t = \alpha_0^T + \sum_{i=0}^{2} \alpha_i^T \cdot \Delta \ln E_{t-i} + \beta^T \cdot \ln P_{t-1} + \sum_{i=0}^{7} \gamma_i^T \cdot \Delta \ln R_{t-i} \qquad \text{(B.1)}$$

For the patent equation, LR tests showed ten lags for public R&D spending and eight lags for private R&D spending are optimal. In other words, the model for patents was specified as

$$\ln P_t = \alpha_o^P + \sum_{i=0}^{10} \alpha_i^P \cdot \Delta \ln R_{t-i} + \sum_{i=0}^{8} \gamma_i^P \cdot \Delta \ln Z_{t-i} \quad \text{(B.2)}$$

For the private R&D spending equation, LR tests revealed that the model with five lags for public R&D spending and two lags for TFP is optimal. The model for private R&D spending is chosen as

$$\Delta \ln Z_t = \alpha_o^Z + \sum_{i=0}^{5} \alpha_i^Z \cdot \Delta \ln R_{t-i} + \sum_{i=0}^{2} \gamma_i^Z \cdot \Delta \ln TFP_{t-i} + \delta \cdot \Delta r_t + \varepsilon \cdot \Delta \ln P_{AGRt} \quad \text{(B.3)}$$

B.2 Instrument Choice

For the two-stage least squares (2SLS) and three-stage least squares (3SLS) estimations, an instrument data set is used to obtain consistent parameter estimates. Two-stage least squares estimation results for the three equations are presented in Appendix B Table B.2.

To choose the relevant instruments, the endogenous variables were regressed on different sets of instruments. The variables that were instrumented are the three dependent variables (TFP, Patent, Private R&D), lagged patent in the TFP equation and Price received by farmers ($\text{Price}_{\text{AGR}}$). The instruments used were lagged values of the three dependent variables, lagged land and lagged land in farms. Different lags of these instruments as well as different combinations of instruments were tried.

When different instrument data sets were tried, it was seen that the estimation results for some variables were sensitive to the choice of instruments. The sign of the

coefficient estimate for patent variable in the TFP equation and the signs of the coefficient estimates of private R&D spending variables in the patent equation were sensitive to the choice of instruments to some extent. This was also true for the interest rate and price received by farmers to a lesser degree. Extension funds, public R&D spending in patent equation and in private R&D spending equation, and TFP in private R&D spending equation were much less affected by the set of instruments used.

B.3 3SLS Estimates

Appendix B Table B.3 presents the three-stage least squares estimation results for the system of equations. The sums of coefficients for explanatory variables with lagged variables are presented. LR tests are conducted for the joint significance of explanatory variables with lags. These are distributed as χ^2 variables with degrees of freedom equal to the lag length. Otherwise, t-test results for significance of individual coefficients are reported.

The first equation has $\Delta \ln TFP_t$ as the dependent variable. The sum of coefficients for the extension funds is negative and LR test for the joint significance of all extension variables indicate that these variables are jointly significant at the 0.10 significance level. The agricultural patent variable has a positive coefficient estimate, although it is not significant. The sum of public R&D spending variables is positive as predicted, but LR test shows that the coefficient estimates are not jointly different from zero at the 0.10 level. The sum of coefficients for extension being negative may be the result of multicollinearity when public R&D spending variables are included in the equation.

The second equation with patent as the dependent variable 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 LR test shows that these variables are jointly significant at 0.10 level. The sum of private R&D spending variables is positive and the LR test reveals that these variables are jointly significant at the same level, 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 though the public R&D variables are not jointly significant at the 0.10 level. Recall that 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. Price received by farmers has a negative and insignificant coefficient. The sum of TFP variables is negative and they are jointly significant. This is contrast to what the model predicted. One thing that must be noted is that in this specification TFP captures the total effect of A(E) and Q. Also, land and labor inputs are not included to avoid multicollinearity, which may cause omitted variable bias.

To incorporate the "business cycles" effects, the U.S. GDP is added as an explanatory variable to the private R&D spending equation. The reason for this modification is the finding that TFP and private R&D spending are negatively correlated, which was contrary to what the model predicted. Appendix B Table B.4 shows the estimation results. It is seen that the sum of coefficients for TFP is now positive and significant same as the ones for the U.S. GDP. TFP now works better as a proxy for the level of available technology and is positively correlated with private R&D spending variable. However, the addition of GDP in the private R&D equation causes the public and private R&D variables in the patent equation to be jointly insignificant.

B.4. Endogeneity Tests

A key implication of the theoretical model is the endogeneity of the private R&D spending. To test whether the endogeneity claim of explanatory variables is supported by the estimation results, a Hausman specification test was conducted. The Hausman test compares seemingly unrelated regression estimates (SUR) with three-stage least squares estimates. For the first specification, the test statistic is 130.60 which exceeds $\chi^2(46)=57.49$ at $\alpha=0.10$ level. So, it rejects the null hypothesis that both SUR and 3SLS estimates are consistent and that only SUR is asymptotically efficient. The alternative hypothesis is that only 3SLS estimates are consistent. For that reason, it provides evidence that using instrumental variables, within 3SLS, is necessary to get consistent coefficient estimates.

Hausman test is conducted for the second specification with the U.S. GDP to see whether data supports the using 3SLS versus SUR. The test statistic is 6.88 which is less

than $\chi^2(49)=63.17$ at $\alpha=0.10$ level. Thus, it does not provide evidence in favor of using 3SLS. This may be due to the large variances in coefficient estimates with 3SLS, which also shows itself in the insignificance of private and public R&D variables in the patent equation.

Comparing these estimation results with the empirical findings of other research is difficult, as the current specification differs substantially from earlier works. Previous work focused on the direct effect of public and private R&D on TFP. In this model, R&D activities affect patents which in turn affect TFP. Most of the previous studies calculated a knowledge stock from R&D spending using a polynomially distributed lag structure. They estimated the effect of knowledge stock on TFP and then derived the coefficient estimates for R&D variables. The best way to compare is to use reduced form coefficient estimates for private and public R&D in the TFP equation from this study with the derived coefficient estimates from previous studies. Although the magnitude of coefficients is hard to compare, the direction of the relationship between the variables is the same. R&D activities contribute positively to creation of patents, which in turn contribute to realization of higher TFP growth rates.

B.5 Internal Rates of Return to R&D

The empirical study most similar to the analysis presented here is that of Makki et al.'s. Both studies use first-differenced stationary data to avoid spurious regression when estimating the impact of R&D on TFP. However, unlike Makki et al. the current study accounts for the endogeneity of key variables (particularly private R&D spending). To this end, a private R&D spending equation was included in the simultaneous system of

equations and instrumental variables were used to correct for the simultaneous equation bias.

For the system of equations, the reduced form coefficients are calculated as follows:

$$\ln TFP_t = \alpha_0 + \sum_{i=0} \alpha_{1i} \cdot \ln E_{t-i} + \alpha_2 \cdot \ln P_{t-1} + \sum_{i=0} \alpha_{3i} \cdot \ln R_{t-i} \quad \text{(B.4)}$$

$$\ln P_t = \beta_0 + \sum_{i=0} \beta_{1i} \cdot \ln R_{t-i} + \sum_{i=0} \beta_{2i} \cdot \ln Z_{t-i} \quad \text{(B.5)}$$

$$\ln TFP_t = \alpha_0 + \alpha_2 \cdot \beta_0 + \sum_{i=0} \alpha_{1i} \cdot \ln E_{t-i} + \alpha_2 \cdot (\sum_{i=0} \beta_{1i} \cdot \ln R_{t-i}) + \sum_{i=0} \alpha_{3i} \cdot \ln R_{t-i} + \alpha_2 \cdot (\sum_{i=0} \beta_{2i} \cdot \ln Z_{t-i}) \quad \text{(B.6)}$$

This way the impacts of public and private R&D investments on TFP are obtained indirectly. In the next step, marginal products of research and extension activities are obtained.

The rate of return to public R&D is 28 percent, whereas the rate of return to private R&D is 3 percent. The rates of return from this study are sensitive to the specification of the equations and the variables included in the system to a certain degree. The rates of return depend on two factors: the coefficient estimates of public and private R&D variables and the coefficient estimate of the patent variable. The patent coefficient in the TFP equation is positive but insignificant. It also shows variation according to the specification of the model. For the system of equations, adding the U.S. GDP variable to the private R&D equation changes the rates of return: 39 percent for public and 10 percent for private. However, in this specification public and private R&D variables are jointly insignificant in the patent equation. Thus, these calculated rates of return are less precise.

When we look at these rates of return, we see that the rate of return to public R&D is higher than private R&D in all cases. This finding is consistent with previous studies. There have been different explanations for this result. One factor can be the existence of an effective extension system facilitating the adoption of public sector's research results. The differences in the type of research conducted by public and private R&D sectors are also important. Public sector has traditionally focused more on basic research, and private sector more on applied technology. To the extent that public research is indeed "basic", it mat well have broader applicability across a range of uses. One other reason can be the fact that public sector makes its findings publicly available, trying to spread new technology and knowledge, whereas private sector is more protective of its research results. This claim is also in line with the earlier finding that public sector contributes more to creation of new patents than the private sector, although public sector does not pursue patent protection as aggressively as the private R&D sector. It also needs to be noted that, any under-investment in public research would tend to put upward pressure on imputed rates of returns – i.e., a reflection of unexploited research opportunities. In contrast, the numbers for private rate of returns may indicate fewer unexploited opportunities among the private sector. Finally, this analysis does not consider any spillovers from research conducted in other countries. If these spillovers are significant contributors to TFP growth in the U.S. agriculture, excluding these variables may lead to omitted variable bias, which may have put an upward pressure on the calculated rate of return in this study.

Table B. 1. OLS REGRESSION RESULTS[a]

	Dependent Variable		
Variable	ΔTFP	Patents	ΔPrivate R&D
Intercept	0.310(0.474)	8.499(0.096)**	0.057(0.026)**
ΔE(t)[b]	-0.140(0.127)		
ΔE(t-1)[b]	-0.010(0.109)		
ΔE(t-2)[b]	0.144(0.095)		
ΔE(t-3)[b]			
ΔE(t-4)[b]			
ΔE(t-5)[b]			
P	-0.034(0.055)		
ΔR(t)[b]	0.277(0.413)	0.363(1.263)	-0.096(0.309)
ΔR(t-1)[b]	-0.707(0.461)	2.039(1.497)	0.825(0.593)
ΔR(t-2)[b]	0.054(0.487)	-0.055(1.543)	-0.025(0.364)
ΔR(t-3)[b]	0.134(0.458)	3.321(1.572)*	-0.246(0.524)
ΔR(t-4)[b]	0.359(0.488)	3.055(1.543)	-0.359(0.386)
ΔR(t-5)[b]	0.316(0.482)	2.898(1.662)	0.617(0.309)*
ΔR(t-6)[b]	-1.068(0.594)*	0.510(1.629)	
ΔR(t-7)[b]	1.066(0.543)*	3.669(1.464)*	
ΔR(t-8)[b]		2.432(1.494)	
ΔR(t-9)[b]		2.657(1.560)	
ΔR(t-10)[b]		4.903(1.348)**	
ΔZ(t)[b]		-0.299(1.141)	
ΔZ(t-1)[b]		-0.300(1.235)	
ΔZ(t-2)[b]		-3.050(1.133)**	
ΔZ(t-3)[b]		1.433(1.204)	
ΔZ(t-4)[b]		-0.476(1.117)	
ΔZ(t-5)[b]		-2.305(1.173)	
ΔZ(t-6)[b]		-1.648(1.137)	
ΔZ(t-7)[b]		-2.462(1.085)*	
ΔZ(t-8)[b]		-1.805(0.983)	
ΔTFP(t)			-0.605(0.318)*
ΔTFP(t-1)			-0.805(0.421)*
ΔTFP(t-2)			-0.670(0.268)**
Δr			-0.307(0.796)
ΔPY			-0.156(0.227)
ΣE	-0.006*		
ΣR	0.431	25.792*	0.716*
ΣZ		-10.912*	
ΣTFP			-2.080*
R^2	0.4582	0.9313	0.5573

a. These are ordinary least squares estimates. Standard errors are in parentheses. ** and * denote significance at the 0.05 level and 0.10 level respectively.

b. LR test for Extension funds is 7.23 $>\chi^2(3)$ =6.25 in TFP equation. LR test for Public R&D is 11.04$<\chi^2(8)$ = 13.36 in TFP equation. LR test for Public R&D is 44.68$>\chi^2(11)$ = 17.28 in Patent equation. LR test for Private R&D is 44.49$>\chi^2(9)$ =14.68 in Patent equation. LR test for Public R&D is 11.51$>\chi^2(6)$ =10.64 in Private R&D equation. LR test for TFP is 12.15$>\chi^2(3)$=6.25 in private R&D equation.

Table B. 2. 2SLS REGRESSION RESULTS[a]

	Dependent Variable		
Variable	ΔTFP	Patents	ΔPrivate R&D
Intercept	-0.173(1.933)	8.531(0.253)**	0.029(0.028)*
$\Delta E(t)^b$	-0.125(0.133)		
$\Delta E(t-1)^b$	-0.021(0.112)		
$\Delta E(t-2)^b$	0.132(0.097)		
$\Delta E(t-3)^b$			
$\Delta E(t-4)^b$			
$\Delta E(t-5)^b$			
P	0.021(0.221)		
$\Delta R(t)^b$	0.241(0.428)	0.148(2.357)	-0.299(0.318)
$\Delta R(t-1)^b$	-0.703(0.486)	2.156(2.645)	0.466(0.389)
$\Delta R(t-2)^b$	-0.020(0.497)	-0.108(2.358)	0.302(0.367)
$\Delta R(t-3)^b$	0.081(0.470)	3.748(3.828)	0.247(0.494)
$\Delta R(t-4)^b$	0.288(0.569)	3.222(2.683)	-0.313(0.426)
$\Delta R(t-5)^b$	0.230(0.483)	2.836(2.483)	0.579(0.326)*
$\Delta R(t-6)^b$	-1.048(0.627)*	0.298(2.791)	
$\Delta R(t-7)^b$	1.011(0.221)	3.689(2.310)	
$\Delta R(t-8)^b$		2.520(2.535)	
$\Delta R(t-9)^b$		2.263(3.720)	
$\Delta R(t-10)^b$		5.098(2.396)*	
$\Delta Z(t)^b$		-2.215(11.913)	
$\Delta Z(t-1)^b$		-0.049(2.128)	
$\Delta Z(t-2)^b$		-3.180(2.064)	
$\Delta Z(t-3)^b$		1.664(1.807)	
$\Delta Z(t-4)^b$		-0.275(2.016)	
$\Delta Z(t-5)^b$		-2.556(2.403)	
$\Delta Z(t-6)^b$		-1.545(1.924)	
$\Delta Z(t-7)^b$		-2.362(1.753)	
$\Delta Z(t-8)^b$		-1.647(1.795)	
ΔTFP(t)			-0.187(0.539)
ΔTFP(t-1)			-0.243(0.279)
ΔTFP(t-2)			-0.496(0.274)*
Δr			-0.841(0.829)
ΔP_{AGR}			-0.062(0.612)
ΣE	-0.041*		
ΣR	0.080	25.870*	0.982
ΣZ		-12.165*	
ΣTFP			-0.926*
R^2	0.4297	0.8445	0.4476

a. These are two-stage least squares estimates. Standard errors are in parentheses. ** and * denote significance at the 0.05 level and 0.10 level respectively.

b. LR test for Extension funds is 6.26 $>\chi^2(3)$ =6.25 in TFP equation. LR test for Public R&D is 9.97$<\chi^2(8)$ = 13.36 in TFP equation. LR test for Public R&D is 37.25$>\chi^2(11)$ = 17.28 in Patent equation. LR test for Private R&D is 30.35$>\chi^2(9)$ =14.68 in Patent equation. LR test for Public R&D is 10.41$<\chi^2(6)$ =10.64 in Private R&D equation. LR test for TFP is 6.47$>\chi^2(3)$=6.25 in private R&D equation.

Table B. 3. 3SLS REGRESSION RESULTS[a]

	Dependent Variable		
Variable	ΔTFP	Patents	ΔPrivate R&D
Intercept	-0.087(1.871)	8.248(0.219)**	0.029(0.028)
$\Delta E(t)$[b]	-0.139(0.132)		
$\Delta E(t-1)$[b]	-0.015(0.111)		
$\Delta E(t-2)$[b]	0.149(0.095)		
$\Delta E(t-3)$[b]			
$\Delta E(t-4)$[b]			
$\Delta E(t-5)$[b]			
P(t-1)	0.011(0.214)		
$\Delta R(t)$[b]	0.216(0.427)	1.290(2.176)	-0.250(0.316)
$\Delta R(t-1)$[b]	-0.711(0.484)	0.394(2.396)	0.529(0.380)
$\Delta R(t-2)$[b]	0.022(0.496)	-1.382(2.193)	0.262(0.365)
$\Delta R(t-3)$[b]	0.092(0.468)	-0.194(3.382)	0.105(0.484)
$\Delta R(t-4)$[b]	0.289(0.565)	0.461(2.437)	-0.410(0.422)
$\Delta R(t-5)$[b]	0.252(0.482)	2.150(2.282)	0.522(0.324)
$\Delta R(t-6)$[b]	-1.120(0.625)*	0.327(2.394)	
$\Delta R(t-7)$[b]	1.077(0.555)*	4.214(2.047)*	
$\Delta R(t-8)$[b]		-0.840(2.111)	
$\Delta R(t-9)$[b]		6.514(3.174)*	
$\Delta R(t-10)$[b]		3.802(1.969)	
$\Delta Z(t)$[b]		11.637(9.892)	
$\Delta Z(t-1)$[b]		0.311(1.747)	
$\Delta Z(t-2)$[b]		-1.151(1.752)	
$\Delta Z(t-3)$[b]		2.170(1.589)	
$\Delta Z(t-4)$[b]		-1.221(1.652)	
$\Delta Z(t-5)$[b]		-0.387(2.013)	
$\Delta Z(t-6)$[b]		-2.307(1.568)	
$\Delta Z(t-7)$[b]		-2.367(1.427)	
$\Delta Z(t-8)$[b]		-2.498(1.495)	
$\Delta TFP(t)$[b]			-0.261(0.526)
$\Delta TFP(t-1)$[b]			-0.096(0.270)
$\Delta TFP(t-2)$[b]			-0.428(0.263)
Δr			-0.357(0.785)
ΔP_{AGR}			-0.176(0.588)
ΣE	-0.005*		
ΣR	0.117	16.736*	0.758*
ΣZ		4.187*	
ΣTFP			-0.785

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 $R^2 = 0.6977$. Instruments are lagged TFP, lagged Patent, lagged private R&D, lagged land, lagged land in farms.

b. LR test for Extension funds is $7.27>\chi^2(3) = 6.25$ in TFP equation. LR test for Public R&D is $10.19<\chi^2(8) = 13.36$ in TFP equation. LR test for Public R&D is $44.47>\chi^2(11) = 17.28$ in Patent equation. LR test for Private R&D is $38.85>\chi^2(9) = 14.68$ in Patent equation. LR test for Public R&D is $9.58<\chi^2(6) = 10.64$ in Private R&D equation. LR test for TFP is $7.41>\chi^2(3) = 6.25$ in private R&D equation.

Table B. 4. 3SLS REGRESSION RESULTS[a]

	Dependent Variable		
Variable	ΔTFP	Patents	ΔPrivate R&D
Intercept	-0.455(1.052)	8.477(0.478)**	-0.011(0.041)
$\Delta E(t)^b$	-0.181(0.124)		
$\Delta E(t-1)^b$	-0.045(0.105)		
$\Delta E(t-2)^b$	0.141(0.094)		
$\Delta E(t-3)^b$			
$\Delta E(t-4)^b$			
$\Delta E(t-5)^b$			
P(t-1)	0.053(0.120)		
$\Delta R(t)^b$	0.236(0.421)	0.586(5.598)	-0.426(0.353)
$\Delta R(t-1)^b$	-0.762(0.476)	0.604(5.906)	0.233(0.471)
$\Delta R(t-2)^b$	0.051(0.480)	-1.413(6.831)	0.403(0.398)
$\Delta R(t-3)^b$	0.100(0.458)	1.071(7.287)	0.948(0.530)
$\Delta R(t-4)^b$	0.333(0.502)	-0.862(6.743)	-0.272(0.483)
$\Delta R(t-5)^b$	0.253(0.478)	2.276(6.719)	0.199(0.404)
$\Delta R(t-6)^b$	-1.171(0.577)*	-1.600(7.284)	
$\Delta R(t-7)^b$	1.194(0.528)**	4.277(8.232)	
$\Delta R(t-8)^b$		-1.519(5.890)	
$\Delta R(t-9)^b$		5.501(7.416)	
$\Delta R(t-10)^b$		0.761(5.659)	
$\Delta Z(t)^b$		1.246(19.847)	
$\Delta Z(t-1)^b$		1.540(5.132)	
$\Delta Z(t-2)^b$		0.301(4.625)	
$\Delta Z(t-3)^b$		4.424(5.035)	
$\Delta Z(t-4)^b$		-0.501(5.122)	
$\Delta Z(t-5)^b$		0.227(5.407)	
$\Delta Z(t-6)^b$		-2.887(5.501)	
$\Delta Z(t-7)^b$		-1.017(5.413)	
$\Delta Z(t-8)^b$		-1.822(4.454)	
$\Delta TFP(t)^b$			-0.204(0.723)
$\Delta TFP(t-1)^b$			0.409(0.315)
$\Delta TFP(t-2)^b$			-0.047(0.303)
Δr			-0.545(0.976)
ΔP_{AGR}			-0.249(0.312)
$\Delta GDP(t)^b$			0.618(0.652)
$\Delta GDP(t-1)^b$			0.909(0.633)
$\Delta GDP(t-2)^b$			-1.056(0.559)*
ΣE	-0.085*		
ΣR	0.234	9.682	1.085*
ΣZ		1.511	
ΣTFP			0.158*
ΣGDP			0.471*

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 $R^2 = 0.7240$. Instruments are lagged TFP, lagged Patent, lagged private R&D, lagged land, lagged land in farms.

b. LR test for Extension is $16.50>\chi^2(3)=6.25$ and LR test for Public R&D is $13.24<\chi^2(8)=13.36$ in TFP equation. LR test for Public R&D is $6.98<\chi^2(11)=17.28$ and LR test for Private R&D is $13.82<\chi^2(9)=14.68$ in Patent equation. LR test for Public R&D is $14.59>\chi^2(6)=10.64$, LR test for TFP is $11.04>\chi^2(3)=6.25$, LR test for GDP is $14.63>\chi^2(3)=6.25$ in private R&D equation.