HISTORICAL REVIEW OF AGRICULTURAL PRODUCTIVITY STUDIES

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ABSTRACT

This document provides a review of the agricultural productivity literature while identifying the various methodologies used and important results for policy formulation purposes. Agricultural productivity is a key driver for the well being of the farmers, the agro-based industry and mankind at large and has important policy implications. Results from the studies imply that productivity growth has been significant at the country level and more recently at the state/provincial/regional level even though there were some difference among states/provinces regarding productivity growth. There is some evidence of agricultural productivity growth slowdown. The literature review also revealed that methods, measures of variables and model specifications used to estimate productivity growth could affect the estimation of productivity growth and its determinants. Regarding method of estimation, overtime there has been a shift from simple indexing to econometric analysis and a complex combination of econometric analysis and non-parametric techniques. Overtime, studies have shifted from using national level aggregate data to regional/provincial level disaggregated data. R&D and technological progress have been identified as the most important determinant of agricultural productivity growth. However, agricultural research funding has been declining. Finally, the difference in productivity growth among countries could be explained by difference in resource endowment, research expenditures (R&D) and the resulting technological progress, and the accumulation of human capital. Hence, increasing funding for agricultural research that increases technical progress should be an essential part of the overall agriculture policies as it could improve agricultural productivity growth significantly. There is also the need for more studies in this important area.

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INTRODUCTION

Over the years numerous studies have contributed to the field of agricultural productivity. This report takes an historical and comprehensive look at the literature on agriculture productivity while focusing on the various methodologies used and discussing the important findings. The document consists of four sections. Section 1 presents the early productivity growth studies (1950s, 1960s, 1970s, 1980s). Section 2 reviews the productivity growth studies in 1990s, while section 3 focuses on the most recent productivity growth studies in the 2000s'. The last section of this document provides the summary and concluding comments. For each era, we identify common elements regarding methodology used, research questions analyzed, research findings and policy recommendations. We also determine how theoretical and empirical research in a given period influences those of the subsequent period(s). This allows us to identify the evolution of research methods used in the analysis of agricultural productivity growth as well as the evolution of different research directions or emphasis. Most importantly, assessing the productivity growth literature provides us great insights into this important research area..

Agricultural productivity is a key driver for the well being of the farmers, the agro-based industry and mankind at large. It is linked to food security, prices, and poverty alleviation in the developing countries (Darku & Malla, 2010). Moreover, food supplies have to be geared to meet the challenges of increasing global population, changes in income, and the resultant changes in diet (Bruinsma, 2009). Hence, research on agricultural productivity is of paramount importance.

Studies reviewed here have used a number of different methods/approaches to measure productivity as well as different concepts/type of productivity. Various methods of estimating productivity growth have yielded different results due to different assumptions and methodological idiosyncrasies. In terms of concepts, productivity growth is classified into three components: technical change, scale effects, and changes in the degree of technical efficiency (Coelli *et al* 2005). Technological progress captures the idea that production function can shift overtime. It refers to the situation in which a firm can achieve more output from a given combination of inputs or equivalently, the same amount of output from fewer inputs. Technical change refers to technological progress in its broadest sense, including advances in physical technologies and innovations in the knowledge base. While, scale effects occur when additional output requires less than proportionate increase in inputs. Finally, technical inefficiency indicates the amount by which actual output falls short of the max possible output. Technical efficiency occurs when resources are used more efficiently by applying practices from the present stock of knowledge.

In terms of approach, productivity measures are broadly divided into partial and total measures. The most common partial productivity measures for the agriculture sector are crop yield and labor productivity, which refer to the amount of output per unit of a particular input. Specifically, crop yield is a measure of output per unit of land, and normally is used to access the success of new production practices or technology. Similarly, labor productivity measures the output per economically active person (EAP). The partial productivity measures could be misleading because they reflect the joint effect of a host of factors and might not give any clear indication of why they change over time. For example, land and labor productivities may rise due to increased use of other inputs such as tractors or fertilizers, or to a move to high value crops.

The methodology used in determining total productivity could be grouped into index numbers or growth accounting techniques; econometric estimation of production relationship; and non-parametric approaches (Data Enveloping Analysis-DEA). Index numbers or growth accounting techniques aggregate all inputs and outputs into input and output indices to calculate total factor productivity (TFP) index, while imposing several strong assumptions about technology. The non-parametric approaches (Data Enveloping Analysis-DEA) use lineal programming technique, and since the model is not statistical, it cannot be statistically tested or evaluated. Finally, the different methods should not be viewed as competitors; there could be important synergies of methods to generate comprehensive results for policy analysis. For example, econometric methods are used to analyze the determinants of TFP obtained by the index method.

1. PRODUCTIVITY GROWTH STUDIES IN THE 1950s, 1960s, 1970s, 1980s.

1.1 SUMMARY

The main objectives of the early productivity growth studies (1950s, 1960s, 1970s, 1980s) were to measure the overall agricultural productivity, the relative efficiency of resources used (e.g., land, labor, capital), estimate the main determinant or drives of productivity growth within a country and among counties (developed DC and less developed countries LDC), assess the role of public research and extension expenditure on productivity, the time lag associated with research expenditures and productivity gains, and to determine the appropriate rate of future investment in public research and extension. Most of the studies used indexing method, while few later studies used econometric method or a combination of indexing and econometric methods to calculate agricultural productivity. The main results in this period were as follows: Productivity growth has been significant. Public research expenditures and extension services contributed to productivity growth. The estimated time lag for farmers to realize the benefit of research expenditures is between 6 and 7 years, peaking at the 8th year. However, it takes between 14 years and 16 years before R&E investment no longer influence output; Technical change was found to contribute 89% of the growth in agricultural output. Additionally, it was shown that most of the difference in productivity growth between developed and developing countries were explained by resource endowment, technology and human capital

Regarding the methods of estimation the literature shows that: adjustments to the measures of variables affect the estimated productivity and different indexes used in the measurement of TFP could lead to different results. Also, the rate of technical change differs based on the estimation method used (e.g., indexing method vs. conventional TFP measures).

1.2 REVIEW

Bhattacharjee (1955) used data from 1948 to 1950 to study agricultural productivity in the world for twenty-two countries[1]. The main focus of the study was to estimate, to some degree, the efficiency of the resources used in agricultural production. The study used data from the United Nations database and a single Cobb-Douglas equation to estimate the agriculture production function. The output variable consisted of net agricultural output for each country, retrieved from national income estimates published by the United Nations and expressed in constant U. S. dollars. The input variables used were: the number of persons employed in agricultural occupations; areas (acres) of arable and pasture land; productive livestock (number of heads); work-stock (livestock used for work); chemical fertilizers (metric tons); and number of tractors. Farmstead and buildings were left out of the inputs due to lack of data, and the quality of human resources engaged in agricultural production was disregarded considering the difficulty in its

[1] The 22 countries were the United States, Canada, United Kingdom, Norway, France, Western Germany, Argentina, Denmark, the Netherlands, Union of South Africa, Eire, Poland, Chile, Puerto Rico, Japan, Italy, Mexico, Greece, Turkey, Egypt, Peru, and India.

quantification. Consumption of manure and other natural fertilizers were also excluded. Due to absence of data relating to horsepower of tractors and other equipment used, the count of tractors was used as a proxy for the input of machinery and equipment.

The main result obtained was that overall agricultural growth during the period 1948 to 1950 was 2.26 % per year. This was similar to the FAO's finding of slightly over 2 % per year (FAO 1953). Among the inputs land had the highest elasticity of production at 0.425, followed by material (0.287) and human resources (0.277). Productive livestock, work-stock, and tractors did not increase the predictive value of the model and the values of their coefficients were statistically insignificant. The coefficients for all the inputs showed diminishing returns, corresponding with general economic thoughts about the nature of returns in agriculture. In addition, the sum of the coefficients was close to 1, implying constant returns to scale.

From the performance of the countries under study, the productivity growth for the whole world was generalized at a rate close to 2.25% per year compared to the estimated annual rate of population growth of 1.22% per year. The author noted that these results have some implication as to the state of food and agriculture in the world. That is to say, if this rate of growth was maintained and the population growth rate was kept below it, then there was no need for alarm.

Griliches (1963) criticized the use of unexplained residual changes as a measure for technical change. Therefore, he put forward an alternative to the conventional production function approach to measuring total factor productivity. This alternate approach was illustrated using a meta-analysis of agricultural productivity growth studies on the United States.[2] The study used a Cobb-Douglas production function and covered the period of 1940 to 1960 for 68 regions

[2] The author brought together the results of a number of studies, including Griliches(1963), Loomis(1960), Jackson (1957), Fox(1962), as well as fourty-three production-function estimates compiled by Elterlich(1961).

of the United States. The focus of this study was on the inputs such as labor, education, machinery, and fertilizer, though the studies included other variables (buildings, other current expenses, and livestock expenses). The author then made adjustments to the measure of variables and compared the results of the two approaches.

The author used a Cobb-Douglas estimated production function with the adjusted series and presented the results in a geometric index base. It was found that using these adjusted series reduced the original estimated productivity increased by one-half (or slightly more). If an economy of scale at the cross-sectional estimated rate was allowed for, then all or somewhat more of the original estimated productivity increase was accounted for.

Evenson (1967) studied agricultural productivity with the objective of estimating the impact of research on agricultural production, and estimating the time lag between research expenditure and its impact. The study was based on data from the state agricultural experiment stations (SAES) and all the states of the U. S. for the period of 1938-1963. Econometric method (iterative nonlinear least-squares estimating procedure) was used to estimate an aggregate Cobb-Douglas production function.

This study used time-series data for U.S. agriculture and cross-section for individual states. The ratio of output to input was used as the dependent variable. Official United States Department of Agriculture (USDA) input indexes were used as input data. Labor was adjusted by an index of years of school completed, weighted by schooling-class income (Welch, 1966). The model also included a weather variable, as constructed by Stallings (1958) and Kost (1964). The results indicated that the effect of research expenditure had a time lag of 6 to 7.5 years on production. The best estimate for the magnitude of the effect of research expenditure on agricultural production was 0.21 with a lag of 6 years.

Hayami & Ruttan (1970) studied agricultural productivity with the objective to understand the causes of the agricultural productivity difference between developed countries (DCs) and less developed countries (LDCs). In all, thirty-eight countries[3] were studied, over the periods 1952 to 1966. Three individual output series were created by aggregating agricultural commodities with the import prices of the United States, Japan, and India. These were then combined into a single output series using a geometric average. The independent variables included labor, land (hectares), livestock, fertilizer (measured by nitrogen, phosphorous oxide and potassium oxide in commercial fertilizers), machinery (measured by tractor horsepower), technical manpower (measured by the number of graduates per ten thousand farm workers from agricultural faculties at above the secondary level), and education. Two measures of the level of education at the primary and secondary levels were attempted, the literacy ratio and the school enrollment ratio. This approach of measuring the leave of education assumed that the same production function could describe the technical possibilities available to agricultural producers in the different countries.

The overall results showed that 95% of the differences in productivity between DCs and LDCs were explained by resource endowment (represented by land and livestock), technology (fertilizer and tractor horsepower) and human capital (represented by education and technical manpower). These three factors were stated to be of roughly equivalent importance. Another result indicated that it was within reach of the LDCs, (with the present land-labor ratios), to enhance their labor productivity four times, attaining similar levels of the older DCs and over half - of recent DCs. A policy recommendation made was that in order to increase the output per

[3] The countries included were Argentina, Austria, Australia, Belgium, Brazil, Canada, Ceylon, Chile, Colombia, Denmark, Finland, France, Germany, Greece, India, Ireland, Israel, Italy, Japan, Mauritius, Mexico, Netherlands, New Zealand, Norway, Peru, Philippines, South Africa, Spain, Surinam, Sweden, Switzerland, Syria, Taiwan, Turkey, U.A.R., U.K., U.S.A., and Venezuela.

worker in the LDCs, even at the current or slightly reduced land area per worker, large doses of investment were required in rural education and in the physical, biological and social sciences.

The results compared with earlier studies. Estimated production elasticity's for land and fertilizer was smaller than the results obtained by Bhatacharjee (1955), However, the authors indicated that their model may be better specified due to the fact that they obtained statistically significant coefficients for livestock and machinery where Bhatacharjee (1955) did not. It was also noted that the resulting aggregate production elasticities in this study were similar to those of Griliches (1964) despite the different nature of the data used.

Christensen (1975) discussed various indexing methodologies to aggregate inputs and output (Laspeyres, Törnqvist and Theil index, approximation of Divisia index, Fisher's ideal index, Paasche index), as well as the value added vis-à-vis the gross approaches in productivity measurement in the TFP estimation.

The study recommended that the "…index numbers representing a transformation function, rather than separate input and output functions…" (p. 914) method proposed by Diewert (1976) for measuring productivity should be tested empirically. Laspeyres index has been stated to be easy to use and interpret, as it holds prices fixed to a base period which makes the changes in quantity clear. Laspeyres index represents a linear production function wherein all factors were assumed to be perfect substitutes. Moreover, Törnqvist index was exact for the homogenous translog production function, which does not require inputs to be perfect substitutes. Christensen (1975), citing Diewert (1976), explained that an index which was an exact homogenous trans log production function and which provides a second-order approximation to an arbitrary twice differentiable homogenous production function was classified as a superlative index. Fisher's ideal index, computed as the geometric mean of

Laspeyres and Paasche indexes, was exact for the quadratic production function and hence a superlative index.

Christensen (1975) study concluded that Törnqvist and other superlative indexes were superior to Laspeyres index as linear production functions were not good approximations of the real world. The Laspeyres and Törnqvist indexes could yield close values only if the time between the base and comparison period was close. Finally, it was recommended that a superlative index should be used to capture the impact of quality change. The method used was a "…superlative index number procedure on the components…" (p. 914). The then adopted methodology of United States Department of Agriculture (USDA) for determining agricultural productivity was criticized for not changing the base period frequently and ignoring the quality aspect in its computation of input indexes. Further, it was recommended that USDA should adopt a superlative index to calculate TFP.

Lu and Liu (1978) used data from 1939 to 1972 to study agricultural productivity growth in the U. S. and evaluated the impact of public research and extension expenditures it. They also estimated the rate of return to R&E investment and benefit to cost ratios. The study covered U.S. agriculture with 1974 to 76 as the base years and projected productivity indexes for 1985, 1990, 1995 and 2000. Regarding econometrics methods, the Almon distributed lag method and Durbin's two-stage procedure were combined to estimate the relevant parameters. An aggregate productivity index for agriculture was used as the dependent variable. The predictor variables included: a lagged production-oriented public R&E expenditure; index of educational attainment of farmers; and weather index (a stochastic variable).

The results of Almon distributed lag and Durbin's two-stage procedure indicated that a 1% increase in R&E expenditure increases productivity gradually at the rate of 0.0037%, reaching a peak in 6 to 7 years. It was also estimated that a 1% change in the weather index changes agricultural productivity by 0.2% in the same direction, and a 1% increase in education index increases productivity by 0.78%.

The study used three different scenarios to project productivity indexes which involve three different productivity growth rates. The first scenario assumed that a low level of R&E was needed to create new technology and therefore, involved maintaining R&E at a zero growth rate. This was referred to as the low technology scenario. The second scenario, or the baseline scenario, assumed that the 1939-72 average real R&E growth rate of 3% per year continued into the future. The third and final scenario, referred to as the high technology scenario, assumed an R&E growth rate of 7% to accelerate research and development of new technologies. For all scenarios the farmers education variable was assumed to increase along an S-shaped curve fitted to the education index data from 1939-72. A normal distribution of the weather index from 1900-72 was used to approximate the distribution of the stochastic weather variable.[4] The cost/benefit ratio was computed by discounting, at 6% per year, a stream of future annual social benefits and program costs from 1978 to 2000.

The results indicated that the annual productivity growth rate was 1% for the low technology scenario and 1.1% for the baseline scenario with an internal rate of return of 10% between the two. The high technology scenario was found to have a productivity growth rate of 1.3% with an internal rate of return of 15% as one moved from the baseline to the high tech scenario, or 25% compared to maintaining the low tech scenario. It was noted that these were less than the historical growth rate of 1.5%. The Lu and Liu (1978) estimated that at the highest

[4] A mean of 100.7 and standard deviation of 11.4 were obtained from the normal distribution of the weather index and incorporated into the simulation.

level of technological change, if the productivity growth pattern had been projected till 2025 (allowing more time for wider dissemination of the new technology), then productivity was estimated to grow at 1.5% per year over the next 50 years (the same rate as the previous 50 years). The benefit/cost ratio under the high technology scenario was 3.4 compared to the low technology scenario and 3.3 compared to the baseline scenario. This meant the benefit were 3.4 times higher than the cost of increasing R&E expenditure growth from 0% to 7% per year and 3.3 times higher than the cost for an increase from 3% to 7% per year.

Knutson & Tweeten (1979) studied agricultural productivity with the objective of estimating an appropriate rate of future investment in public research and extension. They used the production function estimated by Cline (1975) and U.S annual data over the period 1929 to 1972. Productivity was considered to be a function of public sector R&E input in the current and preceding periods, non-production oriented public sector R&E expenditures, an index of educational attainment of farmers and farm laborers, and an index of weather.

The results indicated that, the rates of return of production-oriented research and extension investment was 50% during the period 1939 to 1948, and dropped to 35% for the period 1969 to 1972. These estimates were based on a 16-year lag based on the judgment of agricultural scientists that at least sixteen years was required before R&E investment no longer influences output. It was also noted that at least eight years was required before the maximum effect R&E input on agricultural output was reached. Secondly, the projected rates of return on alternative levels of investment from 1976 to 2015 with the increase in change of research and extension investment was ranging from 39%- to negative values for later years.. According to the experiment, one dollar of expenditure in R&E yielded $5.62 of output during 1976 to 1985, $4.39 during 1986 to 1996, $3.46 during 1996-2005, and $2.78 during 2006 to 2015. Finally, the authors recommended to keep the rate of return on R&E investment near 10% as well as to adopt the following measures: (i) Increase real R&E by 3%, the historic average rate of increase, if demand was expected to grow at a slower rate than 1.5%. (ii) Increase real R&E by 10% for four years and 3% thereafter when demand was expected to grow at 1.5% annually. (iii) Increase real R&E by 10% per year for four to five years if demand was expected to grow at a faster rate (greater than 1.5%), then reduce the rate of increase to 3 to 5% per year. It was noted the above were broad guidelines and that the payoff from increased R&E should be watched from year to year so that suitable changes can be made if needed.

Rao and Chotigeat (1981) studied the relationship between size of land holdings and agricultural productivity. They used the GLS regression technique to estimate a translog function to formalize the relation between output and inputs. The study was conducted using farm level data from several states in South India over the period 1962 to 1970. There were six dependent (output) variables classified into: measure of physical productivity; profitability; and net farm business income. Gross value of output per cultivated hectare and cropped hectare were the measures of physical productivity. Farm business incomes per cultivated hectare and farm business incomes per cropped hectare were the measures of profitability. The last two dependent variables were net farm business income per cultivated hectare and net farm business income per cropped hectare. There were ten input regressors representing land, labor, and capital. They were average size of land holdings; average size of a land fragmentation; total family labor (man-days per hectare); total hired labor (man-days per hectare); current costs on capital equipment (implements, irrigation, fertilizers, seeds, etc.). The capital costs were segregated between those equipment used in traditional modes of farming and those used in modern modes of farming. Capital costs were further segregated between those that performed functions of land (such as fertilizers and high yielding seeds), and those that displaced labor (like ploughs and tractors). Six regressions, one for each of the dependent variables, were run for three models.

The authors observed that there was no systematic relationship between the measures of productivity and land size. Another result indicated that capital had a positive effect, and land and labor, a negative effect on the elasticity of gross value of output per unit of land. However, large capital infusion nullified the negative effects of land, and led to a positive relation between land-size and productivity. It was noted that the elasticity of land with respect to business income per cultivated hectare became positive at maximum values of other cooperating inputs. The authors interpreted this as an evidence of the positive relationship between land size and profitability suggested in earlier studies. A recommendation was made that large-sized farms and higher productivity could go together if hired labor was employed, as opposed to family labor, and more nontraditional (modern) capital was used.

White and Havlicek (1982) investigated the relationship between agricultural research and extension (R&E) and growth in agricultural output in the U.S using data over the period 1943-1977. The study used the Almon distributed lag procedure to regress an aggregate productivity index on lagged values of production-oriented research and extension expenditures, educational attainment of farmers, a weather index and a time lag. The results indicated that, if R&E expenditure was used to reduce the annual growth rate in farm prices, then the rate of return on R&E expenditures declined. The results also indicated that, underfunding of R&E expenditure was very difficult to overcome in the future, even with increased investment in subsequent years. Finally, the study found that R&E expenditure had the highest impact on agricultural productivity in the sixth and seventh year, before declining through to the fourteenth year.

Ball (1985) used the Törnqvist-Theil indexing method to construct input and output indices to study agricultural productivity in the U.S between 1949 and 1979. The main aim was to compare his estimates with those of the U.S Department of Agriculture (USDA). The output variable included animal products excluding dairy; fluid milk and cream; feed and food grains; other field crops; vegetables and melons; and fruits and nuts. The input variables included labor which included paid labor plus an imputed value of self-employed and family labor; capital which includes durable equipment, real property and farm produced durables; and intermediate inputs such as energy, agricultural chemicals, and feed and seed.

The results indicated that total factor productivity (TFP) grew by 1.75% per annum as against 1.70% estimated by the USDA. Secondly, the growth in output was at an average rate of 1.99%, and the growth in input was 0.24%. Thus increases in productivity contributed about 88% of the growth in output, while growth in inputs explained only 12%. The USDA's estimate of growth in output and input were lower at 1.83% and 0.13%, respectively. The USDA's labor input did not account for quality change. It's labor index declined by more than 4% as compared to the 3.17% estimated by the Törnqvist-Theil index. Moreover, since USDA used the market interest rate to assess the returns on capital, it could not be said with certainty whether the true return on capital was reflected.

Capalbo and Denny (1986) studied the connection between gross and net productivity indexes and the implied production structures using data from 1962 to 1978. They also sought to compare Canadian and U.S. agricultural productivity and the relative biases in technical change by analyzing TFP and labor productivity of the two countries. "The net factor productivity measures assumed that technical change affected only the primary inputs (capital and labor) and was Hicks-neutral with respect to the primary inputs" (p. 617). That is to say, materials were separable from capital and labor but not the time trend under partial materials separability. Gross total factor productivity measure assumed technical change affected all the inputs (capital, labor, and materials). This was due, in part, to the time trend being separable from capital and labor but not from materials under partial technical separability.

Combination of non-parametric indexing (Törnqvist approximation to the Divisia index) and econometric method (iterative seemingly unrelated regression) was used to estimate a translog production function for each country. The data for United States and Canada was made comparable either by making changes to the US data, or by selecting comparable data sets. Changes to the US database include aggregating labor into family labor and hired labor, which was then further aggregated into a composite labor index. When calculating service prices for capital, capital gains were excluded. The final adjustment was the exclusion of animal capital from the capital component. Therefore, three broad aggregated inputs were used: capital which includes land, nonresidential structures and durable equipment; labor, both family and hired; and intermediate inputs which includes feed, seed, pesticides, fertilizer, fencing, lime, twine, livestock services, irrigation, fuel, electricity, telephone and miscellaneous material inputs. The results from regression showed that gross and not net output TFP model was accepted for both the countries. That is, the gross output Hicks neutrality hypothesis could not be rejected for both the countries. However, the net output Hicks-neutrality hypothesis was rejected for both countries. Other results from indexing showed that labor productivity and TFP grew faster in Canada than the U.S.

In both countries labor was substituted by capital and material inputs. In Canada, about 50% of labor productivity growth was driven by the contribution of TFP growth. In the United States factor substitution was driving labor productivity. Results of tests for restrictions on technical change showed that in both the countries, the share of labor decreased due to technical change, while the share of capital increased. For both countries the effect of technical changes on materials could not be precisely estimated, and hence the hypothesis of neutral technical bias for materials could not be rejected. The authors note that the results lend support to the use of productivity indexes in measuring grow output total factor productivity.

Capalbo (1988) investigated the contribution of non-constant returns to scale and technical change to TFP growth. The scope of the study was U.S. agriculture during the period 1950 to 1982. An indexing method was adopted to construct TFP while econometric method (iterative seemingly unrelated regression) was used to estimate a translog function to decompose the TFP growth. The outputs variables used were quantity index of crop and livestock products. The inputs were grouped into three categories: a price index of family and hired labor; a price index of land, structures, durable equipment, animal capital, and inventories; and a price index of materials (energy, feed and seed, chemicals, and miscellaneous inputs).

The results indicated that conventionally measured TFP grew at an average rate of 1.56% per year, for the period 1950-82. The growth was not steady but experienced phases of volatility. In the 1960's smaller rates of growth of TFP were present as a result of near zero growth rates in aggregate inputs and slower increases in output growth relative to other years. In the 1970's to early 1980's productivity growth was much higher due to the accelerated growth rate of aggregate output. It is important to note that the growth rates of aggregate output and aggregate inputs cover variation within the composition of the indexes.

The estimated cost-output elasticities from regression analysis showed that the U.S. agriculture experienced decreasing returns to scale. Technical change was found to comprise 89 % of the growth in agricultural output, leaving the rate of growth of aggregate inputs to account for the remaining 11 %. The study concluded that the rate of technical change in US agriculture was understated when conventional TFP measures were used in comparison with the indexing method used in this study.

2. PRODUCTIVITY GROWTH STUDIES IN THE 1990S'.

2.1 SUMMARY

The predominant focus of the productivity growth studies in the 1990s were; to decompose productivity growth into the source components and assess their contribution; to measure the input and output productivities; to assess the role of public research and extension expenditure and private expenditure on productivity; to assess the contribution of technical change on productivity growth; and to compare and contrast the productivity growth in different countries..

During this period studies used a wide range of estimation methods including, index numbers, econometric estimation of production relationship, combined indexing and econometric methods, and non-parametric approaches (Data Enveloping Analysis-DEA). This period marked the emersion of DEA studies of productivity growth, as well as the increased complexity of estimation methods used especially regarding econometric techniques (for example, the use of dynamic optimization framework, seemingly-unrelated regression method).

The main results in this period can be summarized as follows: Productivity growth has been significant. Technical change contributed the most to the TFP growth. Some studies in the previous era underestimated the contribution of technical change to TFP growth. The increase in TFP growth also appeared to be due to increased aggregate output coupled with a decline in growth of aggregated inputs. Canadian agricultural sector was less labor intensive than both the service and industry sector, but capital intensity was similar in all sectors; and the TFP growth in agriculture was similar to the TFP growth in manufacturing.

Regarding agricultural research and extension, it was noted that private sector research, public extension services and farmers' schooling played important role in productivity. Livestock research expenditures in US were too high in relation to crop research expenditures. There was too much public applied research expenditure compared to public pre-technology science research and there were also an underinvestment in crop extension compared to livestock extension. It was recommended that public sector should undertake research that private sector will not undertake due to lack of profit. Moreover, it was shown that the choice of lag length was important in determining the marginal effects of public and private research expenditures on agricultural productivity. Furthermore, it was concluded that publicly provided inputs like agricultural research, road density, and life expectancy play an important role in explaining the differences in cross-country productivity, Hence, it was recommended that investment in health care may be more effective in increasing productivity instead of subsidizing fertilizers or tractors. Some studies concluded that the differences in productivity across countries could be explained by research and average level of education which had a positive impact on productivity growth.

Regarding method of estimation, it was shown that different measures (e.g., different non-parametric measures of agricultural productivity), different methods of estimations, and model specifications could yield different results regarding the productivity growth and the contribution of different productivity sources including technical progress. The input measurement differences and the quality adjustments of inputs could lead to over or underestimating the change in productivity measures because of the over or under-estimation of output. Finally, it was recommended that disaggregated analysis of farm sector productivity growth was essential for understanding the sources of the sector's growth.

2.2 REVIEW

Luh & Stefanou (1991) used indexing and econometric techniques to study agricultural productivity growth in the US during the period 1948 to 1982. They included a varying factor demand and output supply response in the model to imitate dynamic optimization framework. Two output categories were used, crop output and animal products. Crop output includes six output groups: small grains, coarse grains, field crops, fruits, and vegetables. The translog quantity indices and the implicit prices of the five crop output subgroups were used to calculate the implicit price for the aggregated crop variable. The inputs included: labor; intermediate and material inputs; structure; and an aggregated capital variable which includes land, capital, and other capital. The aggregated capital input uses the same aggregation rule as crop output above. The results of econometric estimation indicated that, the dynamically measured TFP grew at 1.50% per annum. Scale, quality-adjusted input growth, and long-run disequilibrium input use contributed 3.44% of TFP growth. While technical change contributed the most to the growth in TFP. It was also found that the studies by Capalbo (1988) and Ball (1985), which assumed long-run equilibrium, underestimated the contribution of technical change to TFP growth. Finally, they found that both capital and labor adjusted sluggishly toward long-run equilibrium levels in response to relative price changes. Physical capital adjusted at the rate of -0.15, which meant it took nearly 7 years to adjust to the long-run equilibrium level. Labor adjusted at the rate of -0.11, meaning that it took 9 years to adjust to the equilibrium level. Their policy recommendation was that asset fixity (sluggish input adjustment) was a predominant factor in the U. S. agriculture productivity.

Thirtle & Bottomley (1992) used the chained productivity indexing method to study U.K agricultural productivity during the 1967 -1990 period. The output variable used comprised of crops, horticulture, livestock, and livestock products. These four outputs were aggregated together using a moving average of their respective shares in total revenue as a weight. The same procedure was used to aggregate inputs together into a single input series, except total cost was used in place of total revenue. The inputs include feed, seed, livestock, fertilizer, machinery, buildings, pesticides, labor, land, and miscellaneous other inputs. Chained partial productivity indices for labor and land were also used in the analysis. These input and output variables were adjusted to incorporate subsidies from the government. Farm-produced capital, such as breeding livestock and work in progress livestock were allocated to the appropriate input category. Similarly, farm-produced intermediate products (feed and seed), which were used as inputs in future production, were subtracted from both sides of the agricultural account.

The results indicated that TFP grew at an annual average rate of 1.88% over the period. The increase in growth appeared to be due to increased aggregate output at a rate of 1.71% per year plus a declining growth in aggregated inputs at a rate of 0.17% per year. The average annual TFP growth rate increased from 1% per year (1967-74) to over 3% per year (1975-84) after U.K. joined the European Community, then dropping to just over 1.5% after 1985. The chained productivity indexes, annual average growth rate (numerical and graphical), and average revenue shares and average annual growth rates of outputs and inputs. In terms of the various output components there was a rapid growth in the crop output index (5% per year), including a 10% increase after 1974. This was in contrast with the 1% per year, or less, growth in the other three outputs (horticulture, livestock, and livestock products). This was explained to be the result of switch over to arable agriculture under the common agricultural practices (CAP) program.

Huffman & Evenson (1992) provided econometric evidence on the contribution of public and private research to U.S. agricultural productivity during 1950-82. The paper focused on four distinct objectives. Firstly, it examined pre-technology and applied public agricultural research from the perspective of their competitiveness and complementary nature. It was believed that the distinction between pre-technology and applied science may be important to developing new technology in the long-run. It was expected that this interaction would have a positive, or complementary, effect on agricultural productivity. Secondly, the paper studied applied agricultural research and public extension. The expectation was that there will be a positive effect on agricultural productivity from public extension and applied science interaction. Thirdly, the paper investigated farmers' schooling and public extension of research, with the expectation that there will be negative interactions between the two.[5] Finally, the paper examines the impact of private agricultural research and public research.

The divisia index was used for productivity decomposition and the seemingly-unrelated-regression method was used for the econometric analysis. The results indicated that in the case of public livestock research, the pre-technology science and applied research coefficient was negative. In other words they substitute one another in affecting productivity (they were not complementary). The author's expected the variables were complementary. In the case of public crop research, these expectations were fulfilled. The coefficient of applied-pretechnology research interaction was positive, meaning they complement one another in affecting

[5] The authors report that there is considerable evidence to support the claim that public extension and farmer's schooling are substitutes in affecting productivity. They source Hayami and Ruttn (1985).

productivity. In the case of crops, public applied research and extensions were substitutes for one another in effecting productivity. The author suggested this result could be attributed to crop technology being more geo-climatic specific, causing public applied crop research and extension to be substitutes. However, in the case of livestock, public applied research and extensions were complementary (as expected). Farmers' schooling acted as a substitute (negative interaction) for public extensions by efficiently processing information about new technology that affected productivity.

The results of productivity elasticity study revealed that the livestock research expenditure was too high in relation to crop research expenditures, and that there was too much public applied research expenditure compared to public pre-technology science research. The positive elasticity for public crop and livestock extension indicated a positive marginal social rate of return for expenditures on commodity-oriented public extension. This also implies underinvestment in crop extension compared to livestock extension. The positive elasticity coefficient for private agricultural research indicated that private sector investment in agricultural research provided a positive return to society.

Several policy recommendations were made. Firstly, private sector research, public extension, and farmers' schooling play important role in productivity. Secondly, livestock research should be organized so that several states share one exceptional program with each of them doing minor adaptive research to further tailor research to local needs. Thirdly, public sector should undertake research that private sector will not undertake due to lack of profit. Finally, agricultural experiment stations must maintain rapport with their clientele group so as to receive support in state legislature for funding.

Chavas & Cox (1992) used nonparametric approach to investigate the effects of research on agricultural productivity in the U.S. using data from 1950 to 1982. Technical progress was modeled as a function of lagged research expenditures. The approach uses a standard linear programming algorithm which makes it empirically manageable. An aggregated output variable was used, as reported in Capalbo and Vo (1988). The input variables were public and private research expenditures, family labor, hired labor, land, structures, other capital, feed and seed, energy, fertilizers, pesticides, and miscellaneous other inputs. The labor inputs were adjusted for changes in education and composition of the labor force, and thus the effects of education were not accounted for. The research expenditure variables entered the model with 15-year and 30-year lags.

The results indicated that the choice of lag length was important in determining the marginal effects of public and private research expenditures on U.S. agricultural productivity. With the 15-year lag, the effect of private research expenditure peaked at 4 years and had no effect after 8 years. The 30-year lag showed that private research has its maximum marginal impact after 15 years, dropping to zero at the 23 year mark. Results with regards to public research indicated that its impact on agricultural output lasted for as long as thirty years under the 30-year lag, with the maximum marginal impact occurring at 23 years. The 15-year lag results showed that public research expenditure affected agricultural productivity for up to 16 years, with its maximum effect occurring at 12 years. Finally, the estimated internal rate of return for public research was 0.28, while that for private research it was 0.17.

Bureau, Färe, and Grosskopf (1995) compared three non-parametric measures of agricultural productivity (the Malmquist, Fisher, and Hulten indexes) using data on 9 nine

European Community (EC) countries[6] and the U.S. during the period 1973 to 1989. The Fisher index was used as a long-run equilibrium index, the Hulten as a short-run index, and the Malmquis, as a distance function index.

The Malmquist productivity index contained one output and six inputs (intermediate inputs, land - hectares, labor – annual worker units, machinery, buildings and animal capital) were considered. The results indicated that the three indexing methods displayed similar patterns across all the countries. The average productivity ranged from 2% in Belgium-Luxembourg to 7% for that of Denmark.

The Fisher index to the Hulten index showed differences. This could be due to the use of wage rates by the Fisher index while the Hulten index used ex post returns for estimating family labor in calculating labor shares. The Fisher index yielded a higher rate of growth in productivity than the Hulten index when wage rates were high and agricultural incomes were low. This was due to the Fisher indexes use of wage rates, which gave a higher weight to an input that was shrinking. When wage rates were low (Greece, Ireland) or agricultural income per self-employed worker was high (Netherlands, US), the Hulten index gave higher rates of productivity than the Fisher index. This divergence could be due to the ability to correct for capacity utilization of labor by the Hulten index, which the Fisher index does not do.

The Malmquist and Hulten indexes were close in the case of Germany. This suggested that short-run disequilibrium was corrected for by using ex post returns for the family, providing a more appropriate measure than wage rate. The use of ex post returns led to overestimating the

[6] The nine EC countries are Germany, France, Belgium-Luxembourg, Italy, Greece, The Netherlands, United Kingdom, Ireland, and Denmark.

marginal contribution of labor to production in France. While in Greece and Ireland, the ex post returns increased the bias of the Fisher effect.

The pronounced differences between Malmquist and Fisher indexes could be due to changes in capital stock. In the case of Greece and Ireland, during a period where output was constant and the stock of capital increased rapidly, the Fisher and Malmquist indexes diverged so that TFP was greater under the Fisher index. In France, Italy, Denmark and the US this divergence occurs when the stock of capital was decreasing. These results suggest the implicit weights given to capital in the Malmquist index were different from the factor shares used in the Fisher index.

The authors also point out that Malmquist index was especially susceptible to outliers. In future research it was suggested to construct Malmquist index using econometric methods which could be compared with “general variable cost frontier approach” (p. 319). Further, Monte Carlo simulation for comparison of indexes was also recommended.

Craig & Pardey (1996) provided a method of adjusting for quality change on measured rates of multifactor productivity (MFP) growth to account for evidence on the effects of quality adjustments in U.S. agriculture. The study was based on the 48 contiguous states of the U.S., during the period 1949 to 1991. The Törnqvist-Theil approximation of the Divisia index was used to construct quantity and price indexes at the state, regional, and national level. Disaggregated data was used within each broad category to account for quality change. Each output index consisted of fifty-four commodities which were differentiated by the state in which the output was produced or 2592 commodities in all (54 x 48) at the national level. State commodities were treated as distinct from one another in order to account for quality differences on the output side. It also allowed the authors to explore the empirical consequences of quality adjustment for productivity measurement by directly comparing the input indices with and without quality adjustment. Conclusions were then drawn as to the effect of quality adjustments on multifactor productivity measures.

The output index included the output categories: livestock, field, fruit and other horticultural crops, nursery and greenhouse products, and implicit quantities of machine hire. Each input index represented fifty-eight types of input differentiated by the state in which it was used. Thirty-two distinct types of labor, differentiated between hours worked by hired workers, family members, and thirty classes of farm operators with various age and education profiles, were used to account for the quality change in labor input. Data on days worked off-farm by farm operators was also factored into the labor input in order to account for the shift towards part-time farming. Pastures or rangeland, non-irrigated cropland, and irrigated cropland were used for the land inputs. The annual state-level cash rent for each type of land was used as a price weight for aggregation. The capital input consisted of seven classes of physical capital (trucks, autos, tractors, combines, pickup balers, mower conditioners, and buildings) and five classes of biological capital (dairy cows, beef cows, ewes, chicken, and sows). The purchased inputs consist of fertilizers (nitrogen, phosphorous, and potash), purchased seed, purchased feed, pesticides, herbicides, fungicides, fuels and oils, electricity, repairs, machine hire and a miscellaneous category.

The results indicated that the average annual growth rate for national output during 1949-91 was 1.58% per year. It was further reported that considering the decline in inputs of almost 0.2% per year, the multifactor productivity (MFP) growth rate average was 1.76%, as compared to 1.91% estimated by USDA for the period 1948 to 1990, and similar to that estimated by Ball et al (1996). The authors reported that the differences between these results were almost entirely due to input measurement differences. The USDA input measurement declines at an annual rate of 0.39% compared to theirs which declined at 0.2%.

Other results from the evidences on the effects of quality adjustment indicated that the decline in total hours of labor dropped from 2.68% to 2.20% at the national level. This indicates that the proportion of hours worked by more experienced and better-educated operators increased. The reduction in total labor hours has been more pronounced in the southern states. For most regions the maximum changes occurred in the 1950s with the exception of the north eastern and Pacific states where the decline peaked in the 1960s. In the Pacific, particularly in California, total labor increased during the1970s and 80ss.

When the quality mix of land was controlled for, the rate of decline in land use was reduced from 0.47% to 0.30% per annum. In the 1980s some high-priced land was taken out of agriculture at a faster rate, while earlier, lands withdrawn from agriculture were of low quality. This quality-adjusted land input increased in the northern and southern Plains states and in the arid western states with the rise in use of irrigated cropland. In the Northern Plains states, when the change in the quality mix of land was considered, it was seen that instead of total acreage dropping at an annual average rate of 0.12%, there was actually an annual average increase in acres in use by 0.26%. The quality-adjusted tractor index (adjusted for average age and horsepower) reduced the annual average growth rate of tractor stocks by 0.4%. However, during the 1970's there was increasing average quality of tractors while the average age of tractors declined. This makes the annual growth rate in the quality-adjusted tractor stock far more impressive than for the unadjusted tractor stock.

It was concluded that with the knowledge of change in input quality, the interpretation of multifactor productivity measures would be more straightforward. This was because knowledge of the change in input quality was required to predict the direction of bias (from pre-aggregation) on measures of productivity. The direction of bias refers to the over or under-estimation of output due to quality adjustments of inputs. This can lead to over or understating the change in the productivity measure.

Lim & Shumway (1997) used cointegration technique to estimate technical change bias in agriculture production by incorporating proxies for technical change that were based on public and private agricultural research expenditures. The study was based on U.S. agricultural production during the period during 1948 to 1991. The empirical analysis involved Indexing (Törnqvist price indexes and implicit quantity indexes) and econometric methods using augmented-Dickey-Fuller (ADF) unit root and Johansen-Juselius maximum likelihood cointegration tests, on quadratic (QD) and translog (TL) functional forms. The data was aggregated into two output categories (crop and livestock) and four input categories (labor, capital, materials, and real estate). In addition, public and private agricultural research expenditures were included as explicit proxies for technical change. A time variable was included to serve as a supplementary proxy for disembodied technical change. The results indicated that the traditional model generated more significant coefficients than the co-integrated model even though the time-series test results demonstrated that the co-integrated model was the more appropriate specification.

The coefficients on research expenditure were significant for 6 of the 16 estimated parameters, at the 5% level, in the co-integrated model, while 11 were significant in the case of traditional models. The signs also reversed in more than half of the cases. For example, in the case of QD co-integrated model, research investments affected only capital input significantly. The signs indicated that private research was capital saving, while public research was capital using. The estimates from QD traditional models incorrectly implied that all input quantities were significantly affected by private research investments, only livestock was not affected by public research, and time affected both livestock and labor. The QD traditional models also gave changed signs for the effects that were significant in both models.

Thirdly, in the co-integrated model the estimates implied that both crop and livestock receipts declined relative to profits with increases in public research investments. Technical change from public research investments was found to be labor and capital saving but material using. However, in the case of estimates from the traditional TL function the implications were almost reversed. Thus the authors concluded that since traditional models failed to properly account for non-stationarity and cointegration in the time series, they generally overestimated the exactness of the statistical relationships. The signs of many parameters were also changed, thus the traditional models were susceptible to spurious estimates.

Fourthly, in the case of elasticities, TL yielded expected signs in both the traditional and co-integrated models. Two of the five QD elasticities had reversed the signs in the two models and only two of the QD elasticities had the anticipated signs. Further, the own-price elasticites of the co-integrated model exhibited higher absolute values compared to the traditional models.

Finally, the QD function was preferable for consistency with the data, while TL function was preferable for consistency of results with theoretical expectations, "for consistency with a twice continuously differentiable profit function (i.e., symmetric cross-price parameters in supply and demand or share equations), or for stable co-integrated economic relationships (i.e., all equations co-integrate and all independent variables)." (p. 552). It was recommended that time-series properties of economic variables need to be accounted for to avoid incorrect inferences. Moreover, selection of functional form and other important model specifications need to be carefully thought out. The authors do not discuss the actual estimation of productivity.

Craig, et al (1997) developed measure of land and labor productivity using a new data set for ninety-eight countries and thirteen geo-political regions over the period 1961 to 1990. The vector graphical technique developed by Hayami & Ruttan (1985) was applied to Cobb-Douglas production function.

They constructed real output index for each of livestock and crop production. National commodity values or price indexes were used to capture real changes over time in each country, with 1980 being the base year. The output and input series for each country were converted into a common currency using an agricultural exchange rate or purchasing power parity (PPP). The input variables used in the study included; land (stock of total hectares of land in agriculture) and labor (economically active agricultural population), fertilizer, tractor horsepower, horsepower of animals primarily used for traction, breeding livestock, road density, real public expenditures on agriculture research per worker, percentage of total agricultural land that was arable or permanently cropped, percentage of arable land that was not irrigated, long term average rainfall, life expectancy at birth, and literacy rates.

It was observed from the statistical analyses that Japan and Europe have the highest measured output per hectare, while it was the lowest in Australia and New Zealand. In the case of developing countries output per hectare was highest in China and the Asia / Pacific. Overall, more-developed countries have higher output per worker, while Asia and sub-Saharan Africa have the lowest. Southern Europe had the highest annual gain in labor productivity (5.4%) while it was the lowest in North America at 3.1%. It was also found that the regions with the highest output per hectare, Asia and Europe, were also some of the heaviest users of fertilizers (measured in equivalent nutrients units of nitrogen, phosphorous and potash). In addition, the regions with the highest output per worker (North America, Western Europe, and Australia and New Zealand) also had the largest amount of tractor horsepower per worker. Finally, the regions with highest land productivity (Europe, Australia and New Zealand, and North America) also have the highest research spending per worker, highest literacy rate, and longest life expectancy. Also, regions with the highest levels of output per worker (Japan and Western Europe) have the greatest road density. These results showed that publicly provided inputs like agricultural research, road density, and life expectancy play an important role in explaining the differences in cross-country productivity.

Results from the regression analyses were quite interesting. Firstly, the overall production elasticity of land was 0.35, and labor was 0.25, which drops when Eastern Bloc countries were included. This means that output increased by 0.35% when land inputs increased by 1% and 0.25% when labor increased by 1%. Secondly, higher output per worker was correlated with higher mean rainfall and greater percentages of arable cropland. Thirdly, road density and real agricultural research expenditures have positive and significant effects on labor productivity. Fourthly, animal traction and road density contain more information about the differences between developing and developed countries. Finally, the unconventional variables (road density, rainfall, the percentage of arable and non-irrigated land, life expectancy, adult literacy, and research expenditures) accounted for 22% to 24% of the variation in labor productivity. A policy recommendation made was that investment in health care may be more effective in increasing productivity instead of subsidizing fertilizers or tractors.

Echevarria (1998) studied the value added of land, labor and capital in agriculture using Canadian provincial data during the period 1971-1991. Revenue was represented by total cash receipts and income-in-kind. Intermediate inputs comprised of electricity, telephone, heating fuel, machinery fuel, fertilizer, lime, pesticides, commercial seed, irrigation, twine, wire and containers, crop and hail insurance, commercial feed, business insurance, custom work, stabilization premiums, and the rebates on machinery fuel, fertilizer, lime, pesticides, commercial feed, heating fuel, electricity and commercial seed. Value added was calculated as the difference between total revenue and intermediate.

The results indicated that the Canadian agriculture sector was less labor intensive than both the services and industry sectors, but capital intensity was similar in all three sectors. Secondly, the value added shares of land, capital, and labor are 16%, 43%, and 41% respectively. Thirdly, the TFP growth in agriculture for the period 1971-91 was estimated as 0.35%, which was stated to be very similar to the TFP growth in manufacturing (0.3%) during the same period. Prince Edward Island (2.49%) and Nova Scotia (1.87%) showed the highest rate of change of the Solow Residuals while Alberta, Saskatchewan, and Manitoba showed rates of change of less than 0.5%.

Arnade (1998) used data on 70 countries over the green revolution period (1961-1993) to estimate technical efficiency and multifactor productivity. The Malmquist index and data envelopment analysis (DEA) was used to compute production efficiency. Agriculture output was represented by the total value of agricultural production in constant international dollars. Non-irrigated agricultural land, irrigated agricultural land, agricultural labor, tractors, fertilizer, and livestock represented the inputs. The 1961-93 data was divided into eleven time periods, each representing a three year average, in order to reduce the effects of weather on production.

The results indicated that Japan, Israel, the Netherlands, and the United States were technically efficient for most years, closely followed by Canada, France and Hungary. The technical change indices grew significantly for most European countries and the United States. It was observed that for most developed countries the technical change indices rose or followed mixed paths (such as Japan's or Australia's), but for many developing countries the technical change indices gradually fell. Some countries such as Bangladesh, Nigeria, Sudan and Zaire experienced sharp drops in their technical change index. In most developing countries agriculture output growth stemmed from increase in input usage. In several countries (for example Brazil, India, Indonesia, Iran, Thailand and Turkey) productivity growth remained negative despite output growth of more than 2.5 per cent a year. This was because growth rate in a key input were higher. It was concluded that technology which improved productivity in a developed country, may not have the same impact in developing countries. It was also noted that subsidies led to decline in productivity.

The non-parametric study analysis was followed by an econometric estimation of productivity growth, using the productivity measure obtained through the linear programming technique as a dependant variable. The predictor variables were average level of education, agricultural research expenditure, and the number of country research and extension agents divided by the number of agricultural employees. Two other variables were included to represent the impact of Consultative Group on International Agricultural Research (CGIAR). The first variable that is the percentage of a country's agricultural output represented by the four crops where CGIAR research has had the most impact on improving seed variety and yields (corn, rice, wheat, potatoes). The second was a dummy variable that takes on the value of 1 if a CGIAR centre for crop development or extension was located in the country and 0 otherwise. To check the impact of traditional endowments two more variables (the second difference ratio of the tractor/labor ratio to the level of traditional inputs, and the second difference ratio of the fertilizer/land ratio to traditional inputs) were added to the regression equation.

The results indicated that CGIAR crops had inverse relationship with productivity growth, the reason for which may be that CGIAR expenditures were targeted to countries with a high percentage of low productivity crops. Research and the average level of education had a positive impact on productivity growth and could explain the differences in productivity across countries, while rapid changes in the tractor and labor ratio had a reverse impact on productivity growth.

Ball, et al (1999) studied agricultural productivity by decomposing U.S.'s productivity growth into the source components, and assess the contributions of each state's productivity growth. The study was based on the 48 contiguous states of the U.S. and at the country level, during the period 1960-90. The Törnqvist indexing method was used to construct output and input indexes. The output consisted of disaggregated crop and livestock data, which included the quantities of commodities sold off the farm, additions to inventory, and quantities consumed by the farm household. The corresponding price for each disaggregated output reflects the value to the producer. Thus, subsidies were added to market values and indirect taxes were subtracted. The regressors included intermediate inputs, labor, and capital.

The results indicated that the relatively smooth, continuous, and persistently positive trend observed for productivity growth hides considerable variation in productivity growth statistics across states and among regions. The annual productivity growth rates range from 0.65% for Wyoming to 2.83% for Mississippi and Louisiana. The TFP growth rates revealed regional clustering (referred to as the cluster effect). The east south and central states had average annual TFP growth rates above 2%, compared to the mountain states which had annual rates below 2%. It was concluded that productivity was the single dominant source of the agricultural sector's economic growth. Input growth continually declined between 1960 and 1990. Labor inputs decreased by nearly 2.8% and capital input by 1.2% during the same period. Finally, the TFP growth has been uneven during the period under study, experiencing particularly weak growth in the sub-period of 1973–79. The study recommended that disaggregated analysis of farm sector productivity growth was essential for understanding the sources of the sector's growth. The authors went on to emphasis an alternative research plan with regards to the repeated regularity of the cluster effect throughout the period 1960-90.

3. PRODUCTIVITY GROWTH STUDIES IN THE 2000S'

3.1 INTRODUCTION

The predominant objectives of the productivity growth studies in the 2000s were similar to the studies in 1990s. Specially, the studies in this era focused on decomposing productivity growth into the source components and assessing their contribution; measuring the input and output productivity; assessing the role of public and private research expenditure and the contribution of technical change on productivity growth; investigating the contributions of research and development (R&D) on productivity growth as well as the contribution of public and private R&D to convergence in state agricultural TFP growth; comparing and contrasting the productivity growth in different states/regions/provinces and in different countries.

Most of the studies used econometric estimation of production relationship. This period marked the emersion of the Bayesian econometrics in the productivity analysis as well. The number of studies in this period that used non-parametric approaches, and combined different estimations methods (e.g., indexing and econometric methods; indexing, DEA and econometric methods) increased, while fewer studies used index number approaches alone. More studies used disaggregated data (for example provinces, states, regions) in the decomposition of productivity growth. The main results in this period are as follows:. Productivity growth has been significant at a country level and at state/provincial level even though there were some differences among states/provinces regarding productivity growth; Some evidence of agricultural productivity growth slowdown; State agricultural TFP levels were not converging across all states of the U.S, and the spillover effects of public agricultural research on TFP growth rates convergence were regional rather than national; Agricultural research and extension had a positive impact on state agriculture; R&D also had a significant contribution to TFP growth, however, it was shown that R&D expenditures have little or no influence on productivity growth rates beyond twenty years; finally, it was concluded that there was a slowdown in the growth in agricultural investment.

Regarding Canada, it was found that growth in crops was faster than growth in livestock, though livestock output growth rate increased while crop output growth rate decreased. Technical change contributed the largest to productivity growth in crops, while the scale effect contributed the largest to productivity growth in livestock.

3.1 REVIEW

McCunn & Huffman (2000) studied the nature of the convergence in state agricultural TFP growth rates and investigated the contributions of public and private research and development (R&D) to this convergence. The study was based on the agricultural production of forty-two U.S. states during the period 1950 to 1982 (the New England states, Alaska and Hawaii were excluded as they accounted for a small portion of US farm output). The period was significant because of interest rate deregulation and developments in genetic engineering of plants and animals. The study adopted indexing (Törnqvist-Theil quantity indexes for input and output) and econometric modeling (OLS and maximum likelihood regression). The output index was constructed from twenty-six crop and eight livestock categories. The input categories were fertilizers, seed, land, labor (man hours), capital services (includes service flows plus operating and repair expenses on capital), purchased feed, and feed fed on farms, hay, and miscellaneous inputs. The expected state average prices were used for outputs while actual average prices were used for purchased inputs (i.e., State average hourly wage rate used for farm labor). Capital services was calculated by using a weighted average of the price of repair and operating expenses for capital and the implicit prices of capital services, which included interest and depreciation on the current value of capital.

The results indicated that state agricultural TFP levels were not converging across all states of the U.S. However, there was some evidence of σ -convergence (single TFP level) among the crop subsector in the southern plains and northeast regions, the livestock subsector in the southeast region, and the aggregate sector in the central, southeast and Pacific regions. It was found that β -convergence (steady state rate of growth) existed, although not constant across states. The speed of convergence was 2.1% per year, 0.3% per year, and 1.7% per year, respectively, for the crop, livestock and aggregate sectors. The spillover effects of public agricultural research on TFP growth rates convergence were found to be regional rather than national. Finally, whereas greater farmer education increased the speed of conditional convergence of TFP growth rates because education led to the adoption of new technologies, an increase in private agricultural research slowed the rate of conditional convergence of TFP because private R&D targets the high margin, niche markets.

Acquaye et al (2003) studied agricultural productivity growth in the U.S. using data on forty-eight states over the period 1949-1991. Fisher's ideal indices were used following Divisia indexing procedures in order to reduce bias in the index numbers. The study used disaggregated data that distinguished among 58 types for inputs (classified into land, labor, capital, and purchased (Electricity, purchased feed, fuel, hired machines, pesticides, nitrogen, phosphorous, potash, repairs, seeds, and miscellaneous purchases) and 55 types for outputs (classified into crops, livestock, machines rented out, and returns from conservation reserve program – CRP). Outputs were aggregated using prices as weights, where prices were not available a national price index was used. The paper compared indexing procedures (Fisher's Ideal, Tornqvist-Theil, Laspeyres, and Paasche) to determine the most suitable index for the study. It was found that the Tornqvist-Theil and Fisher's Ideal indices were almost identical throughout the entire period but that the Fisher's Ideal index was preferred. It was then used to calculate Multifactor productivity growth by subtracting the input growth rate from the corresponding output growth rate.

The results indicated that the U.S. agricultural productivity grew by 1.90% per annum between 1949 and 1991. Output growth contributed 1.71% while input reduction contributed 0.19%. . All 48 states recorded some productivity growth. The Delta, Southeast, and Appalachian regions experienced the highest regional productivity growth rates; while the lowest growth rates were in the Corn Belt and Southern Plains regions.

Pfeiffer (2003) examined agricultural productivity growth in the Andean Community. Focusing on the Andean Community (a homogeneous geographic area) helps identify characteristics of the negative productivity growth in agriculture in developing countries specific to geographical, social or political circumstances. The scope of the study was Bolivia, Colombia, Ecuador, Peru and Venezuela during the period 1972 to 2000. The study adopted econometric

(GLS and maximum likelihood procedures for regression) and non-parametric alternatives. A meta-production function was used to assess productivity change. The meta-production function was estimated in three ways – a fixed-effects production function, a stochastic frontier production function, and a nonparametric Malmquist productivity index. The fixed- effects production function was estimated using GLS methods. The stochastic frontier production function uses maximum-likelihood procedures to estimate the parameters which allow technical change and technical efficiency change over time to be simultaneously investigated. The nonparametric Malmquist index was a, non-stochastic index which was formed using linear programming and the Data Envelopment Analysis Program (DEAP). The rate of technological change was estimated using a parametric production function with time series data that includes a time-trend variable. The Total Factor Productivity rate was defined as the rate of change in output that was not explained by the input change, or the sum of technical change (TC) and efficiency change (EC).

The output was measured as the total value of agricultural production. The input comprised of labor (thousands of participants in the economically active population in agriculture), land (thousands of hectares of arable and permanent cropland), fertilizers (thousands of metric tons of nutrient units), tractors (the number of tractors in use), and livestock (thousands of cow-equivalent livestock units as defined by Hayami and Ruttan (1985)). Three inefficiency variables: an estimate of land quality obtained from the USDA, an estimate of wars and violence, and an estimate of civil freedoms, were also included in the estimations in order to explain the differences in performance between countries. The results obtained across various methods were consistent indicating that, unlike previous studies productivity growth in the Andean Community was positive and increased over time. The TFP growth rates estimated (1.52

% per annum) were comparable to that of the growth rates in developed countries. The growth rate ranged from the highest of 2.11percent for Ecuador to the lowest of 1.08 percent for Venezuela. Finally, technical progress, rather than increases in efficiency, was the main reason behind agricultural productivity growth in the Andean Community. The study recommended that in order to understand behavioral differences across the countries and its impact on productivity, variables such as land quality, war and violence, and political freedom must be included in the analysis.

Coelli & Rao (2003) estimated agricultural TFP during the period 1980-2000, for the 93 largest agricultural producers in the world. The study used the Malmquist index and Data Envelopment Analysis (DEA) methods to construct a piece-wise linear production frontier for each year in the sample. The study used crops and livestock output, derived by aggregating detailed output quantity data on 185 agricultural commodities. Six input variables were used, namely, land (arable land, land under permanent crops and the area under permanent pasture), tractors (count), labor (economically active population in agriculture), fertilizer (the sum of Nitrogen, Potassium and Phosphate), livestock (the sheep-equivalent of buffaloes, cattle, pigs, sheep and goats) and irrigation (area).

The results showed that, firstly, an annual growth in TFP growth of 2.1 %, with efficiency change (or catch-up) contributing 0.9 % per year and technical change (or frontier-shift) explaining the other 1.2 %. Asia posted the highest TFP growth (2.9 %), the main factor being the efficiency change growth of 1.9 %. South America posted the lowest growth rate of 0.6 %. Secondly, a productivity reversal (during1980-2000 period) was observed in the phenomenon of negative productivity trends and technological regression reported in some of the earlier studies for the period 1961-1985. It was observed that regions with the lowest mean technical efficiency scores in 1980 (Asia and Africa) achieved the highest increases in mean technical efficiency over the sample period.

For future studies, the authors recommended the following: (i) an examination of the robustness of the results to shifts in the base period for the computation of output aggregates; (ii) the inclusion of pesticides, herbicides and purchased feed and seed in the input set; (iii) an investigation of the effects of land quality, irrigation and rainfall; (iv) utilization of parametric distance functions to study the robustness of the findings to the choice of methodology and (v) make allowances in the model for horsepower of the tractors.

Huffman and Evenson (2006) studied the impact of federal formula or competitive grant funding of agricultural research on state agricultural productivity. The study used an econometric model of total factor productivity using pooled cross-section time-series data over the period 1970-1999. They estimated the parameters using the Prais–Winsten estimator of regression coefficients, and the standard errors were corrected for heteroscedasticity and contemporaneous correlation across states. The results indicated that public agricultural research and extension had a significant positive impact on state agricultural TFP. Furthermore, program funding, like federal formula funding, had a larger impact on agricultural productivity than federal competitive grants and contracts. This observation was in contradiction to President Bush’s proposal to convert the Hatch Act funding into a competitive grant program. It was also found that the social marginal annualized real rate of return on investment of public resources in agricultural research range between 49 and 62%. The rate of return was even higher for public agricultural extension.

Stewart et al (2009) estimated the growth rates of agricultural output, aggregate input use and total factor productivity (TFP) in crops and livestock production and analyze variations in TFP growth between Canadian Provinces and over time. The study used data on the three Prairie

Provinces during the period 1940 to 2004. Superlative indexing method (Törnqvist-Theil index, a discrete approximation of the Divisia index) was first used to construct the TFP and econometric methods were applied on a translog cost function, to decompose the productivity growth.

The dependent variables (output) consisted of livestock (cattle, swine, sheep, poultry, and dairy) and crop (wheat, barley, canola, tame hay, oats, rye, mixed grains, flaxseed, mustard seed, and specialty crops, i.e., sugar beets, potatoes, dry peas and beans, canary and sunflower seed, grain corn, and lentils). Inputs were aggregated into four categories, (i) capital, including machinery and equipment, and livestock inventory; (ii) labor, including paid and unpaid labor; (iii) land and buildings, including cropped land, pasture, summer fallow and buildings; and (iv) materials, including fertilizer, seed, pesticides, feed, artificial insemination and veterinary fees, fuel, electricity, irrigation, and other miscellaneous expenses.

The results indicated that there were strong productivity growth rates in Prairie agriculture during 1940 to 2004, at 1.56 % per annum. The productivity growth explained 64% of the output growth rate of 2.43% per annum. Productivity growth rates were found to be higher during the last 25 years (1980–2004) at 1.80% per annum. During this period output growth remained at 2.38% per annum. Thus 76% of output growth was attributed to productivity growth. Of the three Prairie Provinces; Manitoba showed the highest productivity growth, followed by Saskatchewan, and Alberta with the lowest productivity growth which fell during the last 25 years.

It was also found that growth in crops (2.85%) was faster than in livestock (1.56%). During the 25 years from 1980 to 2004, the livestock output growth rate increased while the output growth rate for crops slightly decreased. Technical change contributed the largest in the estimated productivity growth in crops (Alberta 94.7%, Saskatchewan 84.5%, and Manitoba

80.4%). The scale effect on crops was 16.9% for Manitoba, 16.5% for Saskatchewan, and 4.9% for Alberta. Scale effect on livestock was 51.0% for Alberta, and 62.4% for Saskatchewan. Manitoba's livestock productivity growth consisted mainly of technical change (53.2%), while scale effect was 36.0%. The authors highlighted that the removal of the Crow rate in 1995, which resulted in the lower prices for feed, may have contributed to increase in livestock productivity. The authors also highlighted that despite geo-climatic similarities there was disparity in the productivity growth rates between Alberta and Saskatchewan, which may be due to Alberta's oil and gas resources. The study recommended the strengthening of data management and use of superlative indexing methodology to measure TFP.

O'Donnell (2010) used the data envelopment analysis (DEA) methodology for estimating and decomposing the multiplicatively complete Hicks–Moorsteen TFP index. The study covered eighty-eight developed and developing countries during the period 1970 to 2001. The study adopted non-parametric method, using DEA with multiple linear programs (LPs) to decompose the Hicks-Moorsteen index to understand the causes of changes in TFP. The output variable consisted of crops and animals. Input comprised of land, labor, livestock, tractors and fertilizer.

The results indicated that the average rate of technical change was 1.0%, slightly less than the 1.1% reported by Coelli and Rao (2005). The highest TFP was observed in Nepal during 1970s, Nepal and Zimbabwe during the 1980s, and Nepal and Thailand during the 1990s. Changes in TFP of Australia and U.S. were attributed mainly to output oriented mix efficiency and residual output oriented scale efficiency. The main cause for change in the TFP in New Zealand was identified as output oriented technical efficiency. It was observed that agricultural productivity in Australia, New Zealand and the United States responded to changes in the agricultural terms of trade (TT). The study highlighted that improvements in TT encouraged technically efficient optimizing firms to expand their operations, even to the extent that returns to scale and scope decreased. Thus increases in profitability may be associated with decline in productivity. The study recommended reduction in levels of output price support, removal of input subsidies, increases in tax rates and any other policies that cause deteriorations in the agricultural TT. Improvement in TT can increase productivity.

Balcombe and Rapsomanikis (2010) empirically examined the impact of R&D on productivity, with special emphasis on lag selection. Further, the study aimed to understand potential structural changes in agriculture. Using data on the U. S. agricultural sector covering the period 1889 to 1990, the study adopted a Bayesian model averaging (BMA) with reverse jump (RJ) algorithm, standard autoregressive distributed lag specification with structural breaks, and gamma lag weightings to approximate lag structure when specifying constrained distributed lags. The dependent variable was the percentage rate of change in productivity, while the predictor variable was the R&D expenditure. This data was provided by Huffman and Evenson (1993), and was essentially a TFP series and public sector agricultural R&D expenditures for the period 1889-1990.

The results indicated that R&D expenditures have little or no influence on productivity growth rates beyond twenty years. Sometimes the impact of research on productivity may not have a long gestation period but may have an immediate impact, may fade away after two or three years, and then have a positive impact some ten or more years later. Evidence of the existence structural breaks was inconclusive. Future research was recommended to unearth the dynamic impact of a number of factors that determine productivity; the use of mechanical and chemical patents, which reflect R&D activities of the private sector, as explanatory variables, and the impact of such explanatory variables analyzed through more complex RJ approaches that deal with count data or survival data.

Salim and Islam (2010) examined the importance of R&D and climate change in the agricultural sector using data on Western Australia over the period 1977/78 to 2005/06. The study used indexing (Törnqvist indexes) and econometric methods applied to standard material-augmented Cobb-Douglas production function and standard Solow's growth accounting technique.

TFP indices were calculated using Solow's standard growth accounting techniques (output growth not accounted for by input growth) and by applying Tornqvist indexing methods following Islam (2004). R&D expenditures was obtained by extending the data series obtained from Mullen *et al.* (1996) with figures collected from the Department of Agriculture and Food, Western Australia (DAFWA) DARWA. Cumulative rainfall data, in millimeters, was used as a proxy for the climate variable.

The results indicated that both R&D (long-run elasticity 0.497) and rainfall (long run elasticity 0.506) were strongly correlated with output and TFP growth. Secondly, unidirectional causality existed running from R&D to TFP growth in both long run and short run. With R&D having less impact in the short run, implying a lagged impact on output. The study recommended that public R&D investment and innovation played an important role in accelerating farmers' adaptation to climate change.

Fuglie (2010) presented a comprehensive global and regional picture of agricultural TFP growth between 1961 and 2007 using data on 171 countries. The study adopted indexing (Törnqvist-Theil index) and econometric methods. The output growth was measured using the FAO output index, which was a Laspeyres index, valuing about 195 crop and livestock commodities at a fixed set of average global prices. For inputs, several country-level case studies that had acquired representative input cost data were brought together. Törnqvist-Theil growth accounting indexes of agricultural TFP growth was constructed for these countries. The average cost-share estimates were then applied to other countries with similar agriculture in order to construct aggregate input indexes for those countries. Inputs were divided into five categories – farm labor, agricultural land, livestock, fertilizer, and farm machinery.

The results indicated that, firstly, there was no evidence of general slowdown in sector-wide agricultural productivity. Secondly, accelerating TFP growth and decelerating input growth have largely offset each other to keep the real output of global agriculture growing at slightly more than 2% per year since the 1970s. Thirdly, there was a slowdown in the growth in agricultural investment.

4. SUMMARY AND CONCLUDING COMMENTS

Agricultural productivity is important with regards to economic efficiency, living standards, international competitiveness, economic sustainability, and has important policy implications. Agricultural productivity is also a key driver for the well being of the farmers, the agro-based industry and mankind at large. Over the years numerous studies have contributed to the field of agricultural productivity. This report has taken a comprehensive look at the literature on agriculture productivity from 1950 to 2011 while focusing on the various methodologies used and important results for policy formulation purpose.

The common and leading objectives of the productivity growth studies over the period were: to measure the overall agricultural productivity; to decompose productivity growth into the source components and assess the contribution of each of them; to evaluate the role of R&D; and to measure contribution of technical progress on productivity growth. he studies were also interested in comparing and contrasting the productivity growth in different countries and in different states/regions/provinces in more recent years as well as to reveal the main determinant or drives of productivity growth differences among countries or states/regions/provinces.

Regarding method of estimation, overtime it has shifted from the predominant use of indexing method to econometric analysis and a complex combination of econometrics and other non-parametric methods such as the DEA. During the 1990s most agricultural productivity studies used the DEA and stochastic frontier approaches, while the intensification of the Bayesian econometrics techniques in the productivity analysis occurred in the 2000s. Recently, studies have increasingly used more disaggregated data (for example provinces, states, regions) in the analysis and decomposition of productivity growth.

Studies prior to the 2000s have indicated that using different measures, different methods of estimations, model specifications, and even different measures of variables could yield different results regarding the overall productivity growth and the contribution of productivity source components on productivity growth including technical progress. As a result recent studies have showed that some earlier studies have underestimated the contribution of technical change to TFP growth. Finally, the choice of lag length could be very important in determining the marginal effects of public and private research expenditures on agricultural productivity.

The predominant results of the productivity studies were that productivity growth has been significant at the country level. More recently productivity growth has been significant at state/provincial/regional level as well, even though there were some differences among states/provinces/regions regarding productivity growth. There is some evidence that agricultural productivity growth has slowed down. R&D and technical progress have contributed the most to

TFP growth. However, it was also concluded that there was a slowdown in the growth in agricultural investment. Finally, the differences in productivity across countries could be explained by resource endowment, technology available/research expenditures, and human capital accumulation such as average level of education.

To sum up, productivity growth in agriculture is very important and has significant policy implications. Therefore, measuring productivity growth is imperative but a very difficult task. The measures used to estimate productivity growth affect the magnitude of the estimates, as well as the direction of effects. Hence, the methodology and assumptions used in measuring productivity growth should be chosen with cautious. It is therefore very important to recognize the importance of using the appropriate approach to measure productivity and to understand the sources and nature of productivity growth especially in the agriculture sector. Finally, technical change is an important determinant of productivity growth. Hence, increasing funding for agricultural research that increases technical progress is essential. Private and public investment in agricultural science and technology could improve productivity growth. More investigation is need in this area.

REFERENCES

Acquaye, A. K. A., Alston, J. M., & Pardey, P. G. (2003). Post–War Productivity Patterns in U.S. Agriculture: Influences of Aggregation Procedures in a State–Level Analysis. *American Journal of Agricultural Economics, 85*(1), 59-80.

Arnade, C. (1998). Using a Programming Approach to Measure International Agricultural Efficiency and Productivity. *Journal of Agricultural Economics, 49*(1), 67-84.

Balcombe, K., & Rapsomanikis, G. (2010). An Analysis of the Impact of Research and Development on Productivity Using Bayesian Model Averaging with a Reversible Jump Algorithm. *American Journal of Agricultural Economics, 92*(4), 985-998.

Ball, V. E. (1985). Output, Input, and Productivity Measurement in U.S. Agriculture 1948–79. *American Journal of Agricultural Economics, 67*(3), 475-486.

Ball, V. E., Bureau, J., Nehring, R., & Somwaru, A. (1996). *Agricultural Productivity Revisited*. Paper presented at the International Food Policy Research Institute (IFPRI) Policy Seminar.

Ball, V. E., Gollop, F. M., Kelly-Hawke, A., & Swinand, G. P. (1999). Patterns of State Productivity Growth in the U.S. Farm Sector: Linking State and Aggregate Models. *American Journal of Agricultural Economics, 81*(1), 164-179.

Bhattacharjee, J. P. (1955). Resource Use and Productivity in World Agriculture. *Journal of Farm Economics, 37*(1), 57-71.

Bruinsma, J. (2009). *The resource outlook to 2050: how much do land, water and crop yield need to increase by 2050?* Paper presented at the How to feed the World in 2050, Rome, Italy.

Bureau, J.-C., Färe, R., & Grosskopf, S. (1995). A comparison of three nonparametric measures of productivity growth in European and United States agriculture. *Journal of Agricultural Economics, 46*(3), 309-326.

Capalbo, S. M. (1988). Measuring The Components Of Aggregate Productivity Growth In U.S. Agriculture. *Western Journal of Agricultural Economics, 13*(1), 53-62.

Capalbo, S. M., & Denny, M. G. S. (1986). Testing Long-Run Productivity Models for the Canadian and U.S. Agricultural Sectors. *American Journal of Agricultural Economics, 68*(3), 615-625.

Chavas, J.-P., & Cox, T. L. (1992). A Nonparametric Analysis of the Influence of Research on Agricultural Productivity. *American Journal of Agricultural Economics, 74*(3), 583-591.

Christensen, L. R. (1975). Concepts and Measurement of Agricultural Productivity. *American Journal of Agricultural Economics, 57*(5), 910-915.

Coelli, T. J., & Rao, D. S. P. (2003). *Total Factor Productivity Growth in Agriculture: A Malmquist Index Analysis of 93 Countries, 1980-2000.* Working Paper Series 02/2003. Centre for Efficiency and Productivity Analysis.

Craig, B. J., & Pardey, P. G. (1996). Productivity measurement in the presence of quality change. *American Journal of Agricultural Economics, 78*(5), 1349-1354.

Darku, A. B., & Malla, S. (2010). Agricultural Productivity Growth in Canada: Concepts and Evidences. *Cairn Policy Brief, 21*, 1-11.

Diewert, W. E. (1976). Exact and superlative index numbers. *Journal of Econometrics, 4*(2), 115-145.

Echevarria, C. (1998). A Three-Factor Agricultural Production Function: The Case of Canada. *International Economic Journal, 12*(3), 63 - 75.

Evenson, R. (1967). The Contribution of Agricultural Research to Production. *Journal of Farm Economics, 49*(5), 1415-1425.

Fuglie, K. O. (2010). Total Factor Productivity in the Global Agricultural Economy: Evidence from FAO Data. In J. M. Alston, B. A. Babcock & P. G. Pardey (Eds.), *The Shifting Patterns of Agricultural Production and Productivity Worldwide* (pp. 63-95). Ames, Iowa: The Midwest Agribusiness Trade Research and Information Center.

Griliches, Z. (1963). The Sources of Measured Productivity Growth: United States Agriculture, 1940-60. *Journal of Political Economy, 71*(4), 331-346.

Hayami, Y., & Ruttan, V. W. (1970). Agricultural Productivity Differences among Countries. *The American Economic Review, 60*(5), 895-911.

Hayami, Y., & Ruttan, V. W. (1985). *Agricultural Development: An International Perspective* (2nd ed.). Baltimore: John Hopkins University Press.

Huffman, W. E., & Evenson, R. E. (1992). Contributions of public and private science and technology to U.S. agricultural productivity. *American Journal of Agricultural Economics, 74*(3), 751-756.

Huffman, W. E., & Evenson, R. E. (2006). Do Formula or Competitive Grant Funds Have Greater Impacts on State Agricultural Productivity? *American Journal of Agricultural Economics, 88*(4), 783-798.

Knutson, M., & Tweeten, L. G. (1979). Toward an Optimal Rate of Growth in Agricultural Production Research and Extension. *American Journal of Agricultural Economics, 61*(1), 70-76.

Kost, W. E. (1964). Weather Indexes, 1950-1963. *Quarterly Bullettin of Michigan Agricultural Experiment Station, 47*, 38-42.

Lim, H., & Shumway, C. R. (1997). Technical Change and Model Specification: U.S. Agricultural Production. *American Journal of Agricultural Economics, 79*(2), 543-554.

Lu, Y.-c., Quance, L., & Liu, C.-l. (1978). Projecting Agricultural Productivity and Its Economic Impact. *American Journal of Agricultural Economics, 60*(5), 976-980.

Luh, Y.-H., & Stefanou, S. E. (1991). Productivity growth in U.S. agriculture under dynamic adjustment. *American Journal of Agricultural Economics, 73*(4), 1116-1125.

McCunn, A., & Huffman, W. E. (2000). Convergence in U.S. Productivity Growth for Agriculture: Implications of Interstate Research Spillovers for Funding Agricultural Research. *American Journal of Agricultural Economics, 82*(2), 370-388.

O'Donnell, C. J. (2010). Measuring and decomposing agricultural productivity and profitability change*. *Australian Journal of Agricultural and Resource Economics, 54*(4), 527-560.

Pfeiffer, L. M. (2003). Award-Winning Undergraduate Paper: Agricultural Productivity Growth in the Andean Community. *American Journal of Agricultural Economics, 85*(5), 1335-1341.

Rao, V., & Chotigeat, T. (1981). The Inverse Relationship between Size of Land Holdings and Agricultural Productivity. *American Journal of Agricultural Economics, 63*(3), 571-574.

Salim, R. A., & Islam, N. (2010). Exploring the impact of R&D and climate change on agricultural productivity growth: the case of Western Australia*. *Australian Journal of Agricultural and Resource Economics, 54*(4), 561-582.

Stallings, J. L. (1958). *Indexes of Influence of Weather on Agriculture Output.* PhD Thesis, Michigan State University.

Stewart, B., Veeman, T., & Unterschultz, J. (2009). Crops and Livestock Productivity Growth in the Prairies: The Impacts of Technical Change and Scale. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie, 57*(3), 379-394.

Thirtle, C., & Bottomley, P. (1992). Total Factor Productivity In UK Agriculture, 1967-90. *Journal of Agricultural Economics, 43*(3), 381-400.

Welch, F. (1966). Measurement of the Quality of Schooling. *American Economic Review, 56*, 379-392.

White, F. C., & Havlicek, J., Jr. (1982). Optimal Expenditures for Agricultural Research and Extension: Implications of Underfunding. *American Journal of Agricultural Economics, 64*(1), 47-55.