This is to certify that the
dissertation entitled

ANALYZING DYNAMICS OF TECHNOLOGICAL ATTRIBUTES IN THE CANADIAN SAWMILLING INDUSTRY: NONPARAMETRIC AND PARAMETRIC APPROACHES

presented by

Asghedom Ghebremichael

has been accepted towards fulfillment
of the requirements for the

Doctoral. degree in Forestry

Karen Potter-Witter
Major Professor's Signature

August 7th, 2007
Date

ANALYZING DYNAMICS OF TECHNOLOGICAL ATTRIBUTES IN THE CANADIAN SAWMILLING INDUSTRY: NONPARAMETRIC AND PARAMETRIC METHODS

By

Asghedom Ghebremichael

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Forestry

2007

ABSTRACT

ANALYZING DYNAMICS OF TECHNOLOGICAL ATTRIBUTES IN THE CANADIAN SAWMILLING INDUSTRY: NONPARAMETRIC AND PARAMETRIC METHODS

By

Asghedom Ghebremichael

The goal of this study was to analyze long-term dynamics of technological attributes in the Canadian sawmilling industry over a forty-year period (1961-2000). Specifying the production technology as a function of capital, labor, energy, sawlogs (the sole raw material inputs), and a time trend variable, nonparametric and parametric empirical methods were implemented jointly.

Nonparametric Method: Focusing on the annual level and growth rates of total factor productivity (TFP) and on effects of tax incentives on capital formation and TFP growth, the multilateral index procedure was applied. The average annual growth rate of TFP over the study period was 2.0%. Parametrically, TFP was decomposed into its main sources. Statistically significant results of two regression models that involved (i) a quadratic function in output and (ii) a log-linear functional form of output and a time trend variable revealed that output growth and technological progress were the main determinants of TFP growth. In addition, a simulated analysis of the effects of raising capital cost allowance (CCA) and investment tax credit (ITC) and reducing corporate income tax (CIT) showed that mutually reinforcing effects of the tax incentives could spur capital formation and TFP growth.

Parametric Method: The maximum likelihood estimation method with iterative Zellner-efficient technique was applied to estimate a multivariate regression system of four equations that involved an unrestricted translog form long-run cost function and three of four cost share equations. The long-run, nonhomothetic cost function described the Canadian sawmilling industry's production technology. The Allen elasticities of input substitution indicated that the pairs of labor/capital, labor/energy, capital/ material, and energy/ material, were substitutes, while the pairs of labor/ material and capital/energy were complements. Highly inelastic own- and cross-price elasticities of derived demand for all the inputs indicated that the inputs were treated as "basic goods". Furthermore, it was observed that less than unity elasticity of total cost with respect to output (0.249), a modest measure of scale economies (0.751), and 2.3% cost diminution rate, which is the dual measure of the prime TFP growth.

This joint implementation of the nonparametric method and the parametric method made it possible to use dynamics of multiple technological attributes to fully explore the dichotomy between the vertical shift in the production frontier, realized through technological progress, and the input driven movements along the frontier, realized through technical efficiency improvements. Important policy implications of the empirical findings were highlighted. To rectify the inevitable limitations of the study, long-term future research projects were proposed.

DEDICATION

To my parents, Ghebremichael Tirfe and Etai Zewdu, and to my wife, Gennet Seile.

ACKNOWLEDGEMENTS

This is a product of many helping hands. Although it is difficult to list everyone by name, I just have to say thank you all! But, I have to express my greatest indebtedness to my Guidance Committee (GC) members, each of whom was instrumental to the success of this project. I completed this research under the guidance of four highly respected professors. For invaluable moral and financial support, for contributions to the structure and contents of this dissertation, and for bearing the responsibilities of chairing the GC, I am very grateful to my supervisor, Dr. Karen Potter-Witter. Beyond the call of duty of any member of the GC, Dr. Robert J. Myers, *Distinguished University Professor* of econometrics, took graciously the responsibility of being my technical advisor on the econometric aspects of the study. It was a great opportunity for me to take Professor Myers' graduate level econometrics course; and eventually to work on this research closely with him. My gratitude to him is beyond words can express. For contributions to the contents of the dissertation and for frequent words of encouragement, I thank Dr. Sandra Batie and Dr. Larry A. Leefers, both of whom were members of the GC.

The Michigan State University's Main Library is a huge depository of knowledge. I am thankful to every employee of the Library for the help I received over the years of my study. But, my highest gratitude goes to those staff members of the *Computing and Technology Services Helpline*. They set up a long distance proxy server for me to be able to access the Library from the comfort of my office in Edmonton, Alberta, Canada. I accessed all top scientific journals published and distributed globally. I was able to print every single article relevant to the work. That was a great deal of help, which expedited my research work tremendously. Again, thanks everyone!

For playing crucial roles in building the database, I am very grateful to two experts of Statistics Canada: Mr. Richard Landry, Chief of Capital Stock Section, and Ms. Mychele Gagnon, Senior Economist, Capital Stock Section. For constructive comments on different earlier versions of the manuscript, I am thankful to my friends Dr. David M. Nanang and Dr. Shashi Kant. My intellectual gratitude and debt goes to three prominent professors of economics at The University of British Columbia: Dr. Erwin W. Diewert, Dr. Michael W. Tretheway, and Dr. Tae H. Oum, each of whom motivated and taught me that economic theory, which is not interpreted and implemented with econometrics is of no use to society.

My employer, the Canadian Forest Service (CFS), deserves special credit for the success of my program. Without the full support and encouragement of many individuals at the CFS, I would not have done it. My special gratitude goes to my work supervisor, Dr. Bill White, who commented on an earlier version of the manuscript and played instrumental role when my study leave was being processed. Among other colleagues at the CFS, Dr. Tim Williamson's detailed comments are gratefully acknowledged.

Last, but not least, I am heavily indebted to my wife, Gennet Seile, who made it all happen. We made it, Gennu!

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 INTRODUCTION

1.1 THE CANADIAN FOREST SECTOR: A SHORT PROFILE

Starting with the biological and physical potential of the forest resource-base, this chapter highlights the socioeconomic importance of the sector and the effects of business cycles on its performance over the years.

The Forest Resource-Base[1] In its to the House of Commons, the The Canadian Forest Service (2006b) stated that Canada's forests account for up to 10% of the world's forest cover, about 30% of the world's boreal forest, more than 25% of the world's temperate rainforest, 25% of the world's wetlands, and 20% of the world's freshwater.

Canada's land mass is estimated to be 979.1 million hectares, out of which 402.1 million hectares are forestland and "other wooded land". The remaining 92 million hectares are characterized as "other wooded land", consisting of treed wetland as well as slow-growing and scattered-treed land. Forestland is estimated to be 310.1 million hectares, of which 294.8 million hectares is described as "commercial forest" (The Canadian Forest Service 2005).

Importance and Challenges In 2005, the Canadian forest products sector created 339,900 in direct and 524, 1000 in indirect and induced jobs. In 2004, it contributed Cdn$35.9 billion to the Canadian GDP, slightly higher than that for

---

[1]The information in this section is from three sources of the CFS: (1) *The State of Canada's Forests 2005-2006: Forest Industry Competitiveness*; (2) *The State of Canada's Forests 2004-2005: The Boreal Forest*, and (3) *Selected Forestry Statistics* Canada, available at: http://www2.nrcan.gc.ca/cfs-scf/selfor/default.html,

2003, which was Cdn$33.7 billion. Canada's trade in forest products reached an historic high of Cdn$44.6 billion in 2004.

The sector's role in the diversification and development of community-based economies is also well documented. Researchers at the CFS estimate that the sector supports nearly 350 rural communities throughout Canada. This is in addition to providing significant employment opportunities in large urban centers, such as Vancouver, Montreal and Toronto, where headquarters of the multinational corporations that trade forest products are located. In total, there were 361, 400 direct jobs in the sector in 2004.

However, even though it is one of the major engines that keep the national economy in motion, the Canadian forest products sector is often adversely affected by a variety of market and nonmarket forces. The effects are revealed through industrial relocation, consolidation, mergers, acquisitions, plant closures, and workforce layoffs. Consequently, industrial restructuring and rationalization measures are frequent.

Structural Dynamics Within the forest sector, a number of industries, predominantly the sawmilling industry, have been going through significant structural changes. As firms strived to increase productivity and reduce production costs, a rapid pace of mergers, acquisitions, and mill closures occurred during 2004–2005. Generally, these types of industrial consolidation measures are taken in order to gain efficiency and scale economies.

In addition to the mergers and acquisitions, the Canadian forest sector experienced closures of 68 plants from September 2004 to May 2005. Most of these were pulp mills and sawmill (CFS 2005). These closures were attributed to a number of factors, which include the U.S.–Canada softwood lumber dispute; relatively higher exchange rate of the Canadian dollar to the US dollar; high energy costs; rising costs of delivered logs and high competition from offshore producers.

1.2 THE SAWMILLING INDUSTRY

For the purpose of this study, the sawmilling industry is the 1980 Standard Industrial Classification-Establishments 251 (SIC-E-251), which includes establishments primarily engaged in manufacturing lumber, both rough and dressed, shakes and shingles, and other sawmill and/or planing mill products (Statistics Canada 2005)[2]. That is, the study covers the Shingle and Shake Industry (SIC-E-2511) and the Sawmill and Planing Mill Products Industry (SIC-E-2512).

Lumber is the most important product of the Canadian sawmilling industry. Consequently, timber harvested for sawlogs, the sole inputs for lumber production, increased steadily over the years (CFS 2005): from 32.6 million m^3 in 1940 to 164.4 million m^3 in 2002, while harvest for the other three uses - pulpwood, fuelwood, and special uses declined steadily (Figs 1.1 and 1.2).

The utilization rate of harvested timber for lumber production was high in the 1980s and 1990s (Table 1.1). For example, from an average annual of 34.1 million m^3 (43.1% of the total harvest) during the period of 1940s, it jumped to an average annual of 146.0 million m^3 (more than 87.2% of the total harvest) in the

[2] http://www.statcan.ca/english/Subjects/Standard/sic/sice80-classe.htm#251 , accessed August, 2006.

1980s. In 2001 and 2002, the latest years for which data were available, sawlogs accounted for 83% and 84%, respectively (Table 1.1).

Table 1.1. Average annual of Canadian timber harvested by end-use (million m^3)

Period	Sawlogs	Pulpwood	Special Use	Fuelwood	Total Harvest	Share of Sawlogs (%)
1941-50	34.1	26.5	2.1	16.4	79.2	43.1
1951-60	44.1	36.4	2.0	8.5	90.9	48.5
1961-70	63.2	36.0	2.0	5.2	106.2	59.5
1971-80	95.2	40.0	1.3	4.0	140.1	68.0
1981-90	146.0	30.0	2.5	5.0	167.5	87.2
1991-00	146.0	30.0	2.5	5.0	182.8	79.9
2001	154. 4	23.1	5.4	3.0	185.9	83.1
2002	164.4	26.0	3.3	3.0	196.6	83.6

Source: *Selected Forestry Statistics Canada* (Table I-1). Refer footnote 1 (previous page).

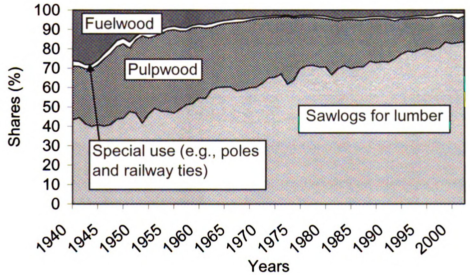

Figure 1.1. Shares in total Canadian timber harvested by end-use: 1940-2002.

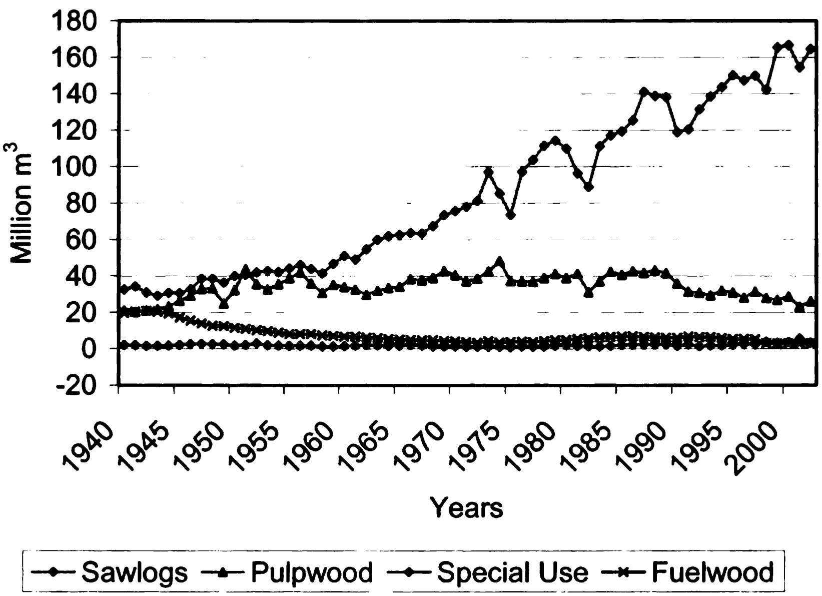

Figure 1.2. Trends in Canadian timber harvested by end-use type: 1940–02.

The rapidly rising trend in timber harvested for sawlogs shows the economic importance of the Canadian sawmilling industry. However, as pointed out above, the industry has gone through several business cycles (Figs. 1.3 through 1.5).

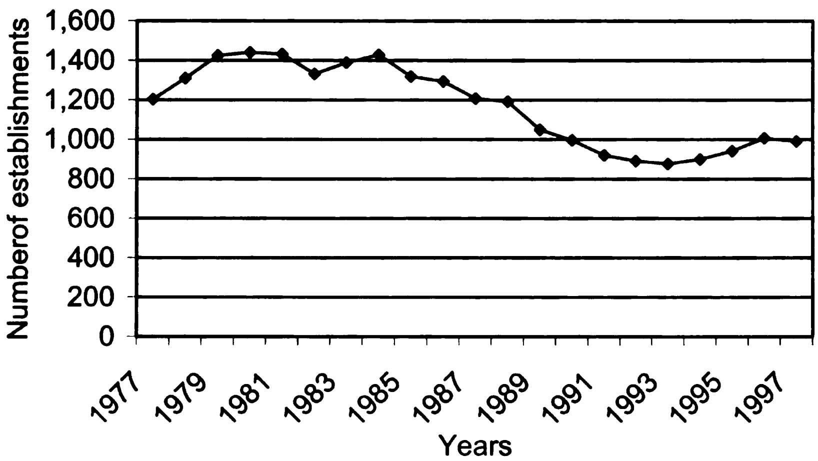

Figure 1.3. Number of establishments in the Canadian sawmilling industry.

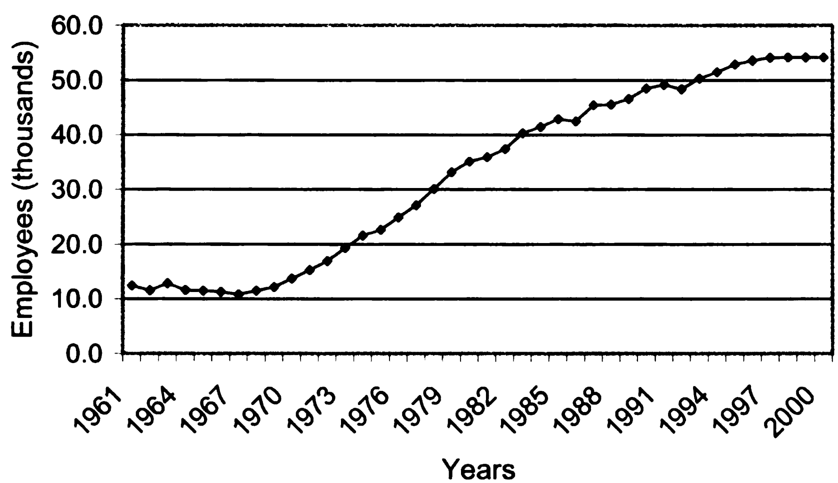

Figure 1.4. Historical trends in employment in the Canadian sawmilling industry.

The ten-year historical trends in four major indicators - (a) the number of establishments, (b) the number of employees, (c) total salaries and wages, and (d) total value added, illustrate the effects of business cycles. From 1977 to 1978, for example, the number of establishments and employees increased by 9%

(from 1,203 to 1,310) and 10% (from 62,199 to 68,616), respectively (Figs. 1.3 and 1.4). But, from 1988 to 1989, both the number of establishments and the number of employees declined by nearly 12% and 5%, respectively.

While the growth rate of total salaries and wages was relatively slow over the two decades of 1977 to 1997 that of total value added rose rapidly, with some fluctuations (Fig. 1.5).

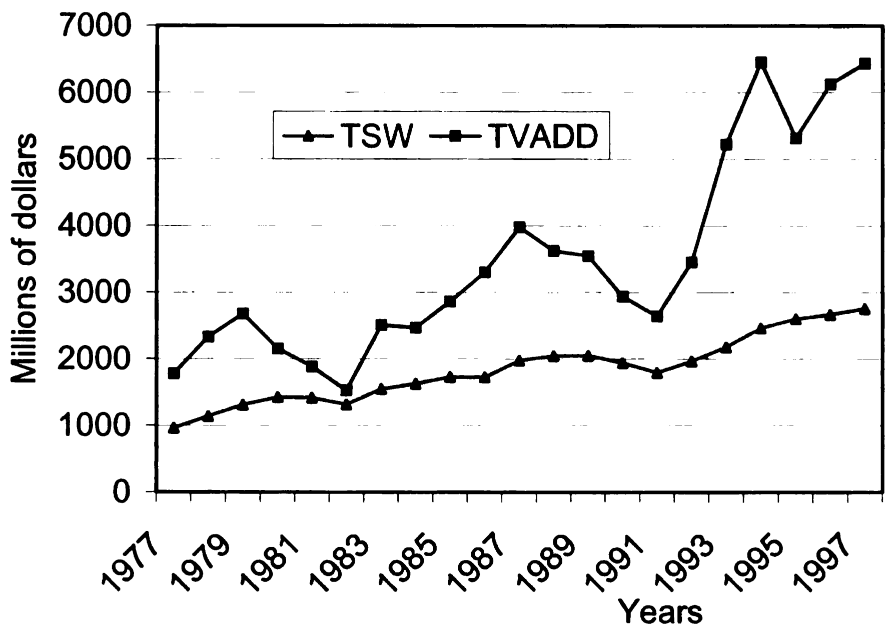

Figure 1.5. Total salaries and wages (TSW) and total value added (TVADD) in the Canadian sawmilling industry.

In summary, the Canadian sawmilling industry, which is the dominant industry within the forest sector, went through a variety of industrial restructuring measures that involved acquisitions, mergers, and plant closures from the early 1970s to the late 1990s. The rapidly rising trends in timber harvested for sawlogs and in total value added appear to indicate that the industry expanded production operations (Figs. 1.1, 1.2, 1.5 and Table 1.1). Whether or not this led to economies of scale is an empirical issue, which is examined in this study (Chapter 6).

1.3 RATIONALE: PROBLEM STATEMENT AND KNOWLEDGE GAP

Public policy papers (e.g., CFS 2005)[3], business reports and the media commonly allege that the following proximate factors have negative impacts on productivity and, hence, competitiveness of the Canadian forest products sector: (i) new sources of timber supply from low cost, fast growing plantations in the Southern Hemisphere; (ii) higher productivity levels achieved by Canada's traditional competitors in the marketplace; (iii) technological advances producing specialized, engineered products (e.g., aluminum, composite Material, and plastic products) that are substitute for solid wood products; (iv) globalization of the marketplace; (v) environmental quality regulations; (vi) international trade disputes – particularly the frequent softwood lumber trade dispute between the United States and Canada; (vii) Canada's international trade and environmental treaty obligations; (viii) rapidly declining commercially viable national timber supply; and (ix) the demand Canadians place on their forest resources for a variety of goods (e.g., paper, lumber, and plywood) and services (e.g., recreational activities, carbon sequestration, aesthetic values, wildlife habitat, and soil and water conservation).

It is true that all these peripheral issues influence the overall economic performance of the sawmilling industry to some extent. But, the extensive research literature shows that it is the dynamics of multiple attributes of the production technology that primarily determine performance of an industry. This

[3] See footnote 1.

is particularly the case for the Canadian sawmilling industry, which operates in highly competitive international markets.

As described earlier, the sawmilling industry plays a very important role in the Canadian economy. Given its importance, however, not much scientific research has examined its production and cost structures, and thereby its productivity performance. The available literature, most of which is from the 1980s, shows that there is a wide gap of knowledge in terms of analytical depth and statistical adequacy. For example, Nautiyal and Singh (1983) used annual data for the 29-year period of 1952-1980 and estimated Cobb-Douglas (CD) and constant elasticity of substitution (CES) forms of a restricted profit function for each industry. They specified the industry's production technology as a function of capital stock, labor, and roundwood only, without taking into account the role of energy. The authors concluded that the CD form represented the lumber and the veneer and plywood industries best, while the CES explained the pulp and paper industry. Several other studies that used annual data covering less than 20-year data-points estimated transcendental logarithmic (TL) forms of cost functions to examine various aspects of the Canadian sawmilling industry's production technology during the early and mid-1980s (Section 6.4).

Using the multilateral index procedure, Ghebremichael et al. (1990) conducted an inter-regional comparative analysis of productivity in the Canadian sawmilling industry. These researchers were unable to carry out total factor productivity (TFP) analysis, but estimated "variable factor productivity (VFP)", which is an aggregate quantity of output per unit of aggregate quantity of the variable inputs: labor, energy, and Material. More recently, Latta and Adams (2000) and Williamson et al. (2004) estimated restricted profit functions to analyze derived demand for inputs and supply of outputs for the Canadian sawmilling industry.

This study differs from previous studies in several ways, including (i) coverage of a longer time frame, a forty-year period (1961-2000), (ii generation of a price for capital services, using the perpetual inventory method, (a methodology that accounts for opportunity cost of various capital assets); (iii) database structure that details the multi-output and multi-input nature of the industry; and (iv) a joint implementation of two major empirical methods, the multilateral index procedure and econometric techniques, by which a wide range of nonparametric and parametric empirical results were computed, interpreted, and their policy implications explained.

The joint implementation of the two methods has provided comprehensive information on the nature and dynamics of the industry's technological attributes. It was learned that "our ignorance" of the meaning and the sources of total factor productivity (TFP) was dispelled, because the empirical results from both methods illustrated the dichotomy between the vertical shift in the production function, explained by the level and growth rates of TFP, and the input driven moment along the function, explained by various parametric results.

1.4 GOAL, HYPOTHESIS, THEMES, AND RESEARCH QUESTIONS

Goal: The goal of this study was to analyze long-term dynamics of technological attributes that characterize the Canadian sawmilling industry's production technology. To that end, the following hypothesis was constructed; major thematic areas were identified; and guiding research questions were formulated.

Hypothesis:

Over the forty-year study period (1961-2000), the sawmilling industry went through several adjustments, such as mergers and plant closures; made investments in R&D and/or purchased a variety of technologies, such as machinery, equipment, and computer hardware and software; and, after considering submissions of national organizations, such as the Canadian Chamber of Commerce (2004), the Forest Products Association of Canada (2006), and the Institute for Competitiveness & Prosperity (2006), the Canadian government provided tax incentives in order to spur capital formation and productivity.

Hence, it was hypothesized that these enabling conditions resulted in technical efficiency improvements and technological progress, which could be inferred through and gauged by the scale of and the trends in the nonparametric and parametric empirical results, such as total factor productivity, cost diminution rate (the dual measure of total factor productivity), economies of scale, capital formation and intensity, and returns to scale.

Economists make clear distinction between technical efficiency improvements and technological progress. Technical efficiency improvements are revealed through increase in output without raising quantities or qualities of inputs. They are believed to be results of various factors, such as learning-by-doing, better management practices, structural adjustments made against shocks external to the industry, and innovation and diffusion of new technologies invented elsewhere. Technological progress, on the other hand, is an increase in output, which is realized through improvements in quality of inputs (e.g., human capital through education and physical capital through inventions and innovations) and investments in R&D (Intriligator 1965 and Romer 1990).

Thematic Areas and Guiding Research Questions:

Theme 1: Contributions of technical and technological progress to productivity

Trends in the levels and the growth rates of total factor productivity (TFP) are good indicators of technical and technological improvements. Two questions that deal with TFP are examined under Theme 1. The first question focuses on the levels and growth rates of TFP: *what were the trends in the levels and the growth rates of gross TFP in the Canadian sawmilling industry over the forty-year study period?*

The second question deals with the sources of growth of the gross TFP: *what were the main sources of TFP growth?*

Theme 2: Multiple parameters that characterize the Canadian sawmilling industry's production technology

To examine technical improvements and technological progress over the study period, the following conditions were postulated: (i) presence of economies of scale and increasing returns to scale; (ii) less than unitary elasticity of cost with respect to output, suggesting production cost increased at a lower rate than that of output; (iii) combined contributions of both scale effects and rate of output growth to TFP growth; and (iv) measurable rate of cost *diminution*, which is also interchangeably referred to as a dual measure of the primal TFP growth or a measure of disembodied technological progress.

In addition, own- and cross-price elasticities of derived demand for inputs to examine substitutability or complementarity between pairs of inputs; input substitution elasticities to observe the degree of ease in substituting one input for another; and nature of technological change-bias to evaluate effects of factor-saving and Hicks-neutral changes on employment and capital formation were used to characterize the industry's production technology.

Theme 3: *Tax incentives to spur capital formation and productivity*

Taxation policy instruments, such as capital cost allowance (CCA)[4], investment tax credit (ITC), and corporate income tax (CIT) influence capital formation and productivity performance of an industry. Given the fact that this research covers a forty-year period, during which several monetary and fiscal policy changes occurred, assessing impacts of changes in fiscal and monetary variables on capital formation and on TFP growth provides useful information for policy making. Hence, the following research question was explored:

What would have been the effects of annual increases in the rates of CCA and ITC and annual reductions in the rate of CIT on capital formation and TFP growth?

---

[4]CCA is a tax deduction that Canadian tax laws allow a business to claim for the loss of capital assets' values due to wear and tear or obsolescence (Revenue Canada 2006): http://www.cra-arc.gc.ca/menu-e.html, accessed October 4, 2006.

1.5 ORGANIZATION OF THE STUDY

The study is organized into eight chapters. Highlights of the Canadian forest sector's economic profile; the rationale for the study; and the hypothesis and the guiding-research questions, classified under three major themes, are discussed in Chapter 1. The various theoretical foundations of this study are explained in Chapter 2. The nonparametric and parametric empirical methods and the database are detailed in Chapters 3 and 4, respectively. In Chapters 5 and 6, empirical results of the nonparametric and parametric methods are discussed, respectively. The main previous chapters are summarized in Chapter 7. Finally, conclusions, policy implications, the study's limitations, and future research directions are provided in Chapter 8.

CHAPTER 2 THEORETICAL FRAMEWORK

The preceding chapter has established the general direction of the study. This chapter prepares the theoretical foundation for building the specific empirical models that are explained in Chapter 3.

By necessity, this research uses concepts and techniques developed under a wide spectrum of theories. Accordingly, several theoretical topics that are particularly pertinent to this study are explored briefly in this chapter. The topics include key conceptual technical terms, the neoclassical exogenous growth theory, the endogenous growth theory, imperatives of effective institutional arrangements, and path dependent technological progress. Finally, several links between the theoretical framework in this chapter and the specific methods described in Chapter 3 are summarized.

2.1 KEY CONCEPTUAL TERMS

In the economics of production, the following terms are used to describe various attributes of technology: productivity, production frontier, technical efficiency, allocative efficiency, technical change, scale economies, total factor productivity, and feasible production set. Although these terms seem to be deceptively very elementary for the specialist, it is appropriate to describe each term here for the sake of clarity and ease of reference.

Productivity: There are two types: partial factor productivity (PFP), which is aggregate output (in the case of a multi-output firm or an industry) per unit of the quantity of a single input, such as labor; and total factor productivity (TFP), which is aggregate output per unit of the aggregate quantity of all inputs (e.g., labor, capital, energy, and Material).

Analyzing this aspect of the industry's production technology is a major part of this research. The methodology is detailed in Section 3.2 (Chapter 3).

Production frontier: Bounding all feasible production sets, i.e., all input-output combinations, the production frontier represents maximum attainable output from given set of inputs (Fig. 2.1)

Technical efficiency: Many members of the media, policy makers, and the general public use productivity and technical efficiency interchangeably. This, unfortunately, is wrong. To clarify the misconception, let there be a short-run production function, with fixed capital input, K_0, and a variable labor input, L, as specified in Eqn. (2.1):

$$Q = f(K_0, L) \tag{2.1}$$

Based on this short-run production function, these relationships can be expressed geometrically (Fig. 2.1):

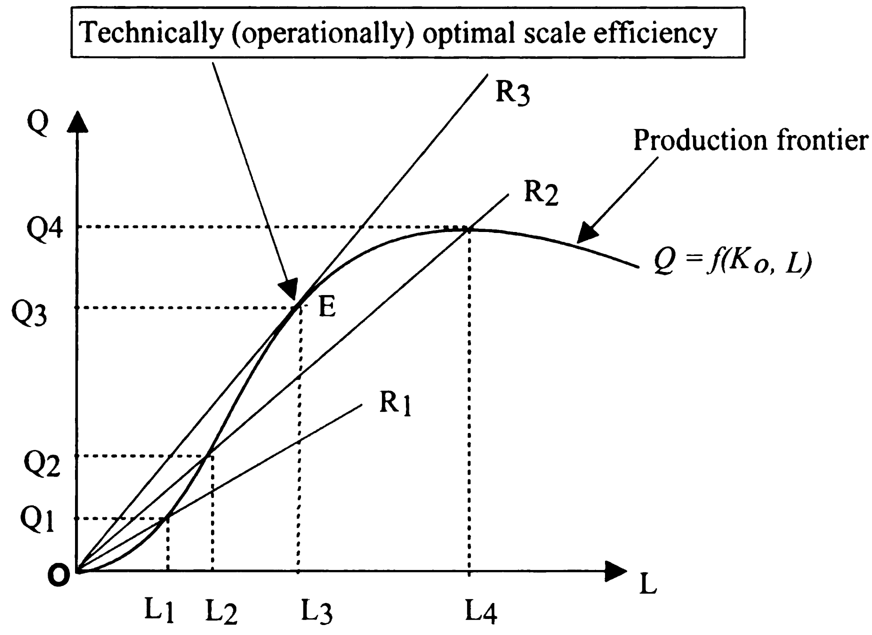

Figure 2.1. Production frontier, productivity, technical efficiency, and scale economies

In Figure 2.1 slopes of the rays OR_1, OR_2, and OR_3 represent average productivity of labor, i.e., $APL_i = \frac{Q_i}{L_i}$, the steeper the ray, the higher the APL_i. Thus, output Q_3, with labor input L_3, at the point of tangency, point E, is the maximum possible output. At that point of tangency, APL is equal to the marginal product of labor (MPL), described by the slope of the total production frontier. That is,

$$MPL \equiv f_L = \frac{\partial Q(.)}{\partial L} = \text{Slope of the total production frontier} \qquad (2.2)$$

Thus, the point of tangency, point E, indicates technically optimal scale of operation (Fig. 2.1). However, given the fact that changing a firm's scale of operation takes time, technical efficiency and productivity are often given short-run and long-run interpretations. That is, dynamic interpretation of productivity involves possible technological progress, which is revealed through an upward vertical shift in the production frontier (Fig. 2.2).

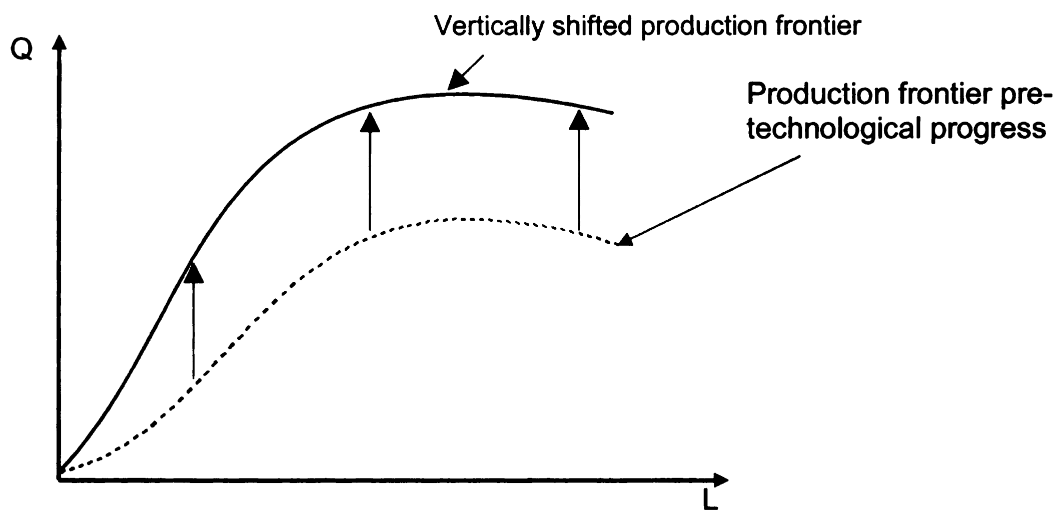

Figure 2.2. Technological progress over two periods

Allocative Efficiency: This refers to a least-cost combination of inputs (e.g., K and L) to produce a given level of output, Q, under given prices of the inputs. It is illustrated in Figure 2.3 and simple derivations that follow:

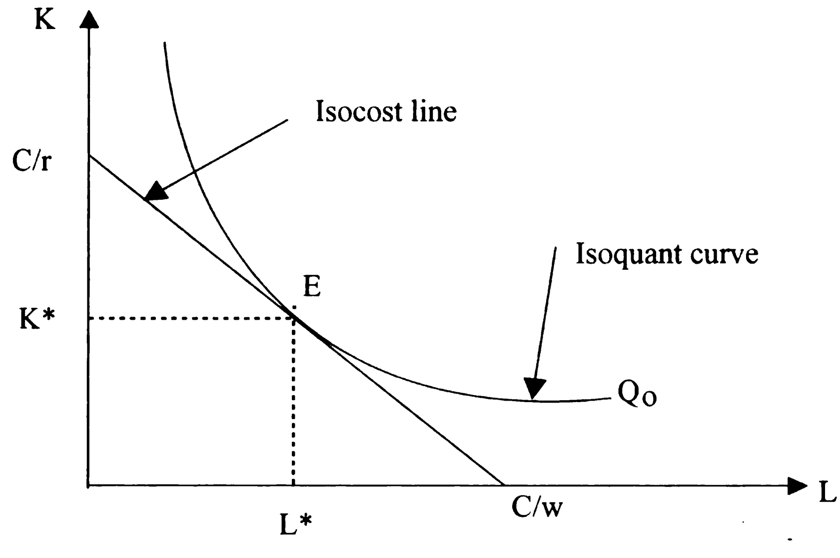

Figure 2.3. Allocative and technical efficiency

$C = rK + wL$ is a total cost, with r = capital rental price and w = labor price.

At point E, the point where the isocost line and the isoquant curve are tangent to each other, their respective slopes are equal, meeting the following conditions for allocative and technical efficiency (Fig. 2.3):

$$dQ_o = 0 = f_L dL + f_K dK \Rightarrow -\frac{dK}{dL} = \frac{f_L}{f_K} = MRTS_{LK} \qquad (2.3)$$

This condition is for the isoquant curve at point E.

And, for the isocost at the same point:

$$-\frac{dK}{dL} = \frac{w}{r} \qquad (2.4)$$

Thus, producer's equilibrium is attained at point E, where $MRTS_{LK} = \frac{w}{r}$.

That is, $MRTS_{LK}$ = marginal rate of technical substitution of labor for capital, must be equal to the input price ratio for allocative and technical efficiencies to be attained (Fig. 2.3).

2.2 THE NEOCLASSICAL EXOGENOUS GROWTH THEORY

The scope and complexity of the research on technological progress and economic growth are described in this section. As an area of research, growth theory is vast and diverse. For example, Jaffe et al. (2001) identify the following ten major subject areas of research: (i) the theory of incentives for R&D; (ii) the measurement of innovative inputs and outputs; (iii) the analysis and measurement of positive externalities, i.e., *spillovers* of R&D; (iv) the measurement and analysis of productivity growth; (v) the process of diffusion of new technologies; (vi) the effects of market structure on invention and innovation; (vii) the failures of markets for inventions and innovations and the challenges of designing effective institutional arrangements; (viii) the socioeconomic impacts of publicly funded research projects; (ix) the economic effects of the patent system; (x) the role of technological progress in endogenous macroeconomic growth.

Solow's (1957) seminal paper, *Technical Change and the Aggregate Production Function,* has direct relevance to this study. In building his macroeconomic production function model, Solow (1957) made the following seven principal assumptions: (i) a national economy characterized by a constant returns to scale production technology; (ii) perfectly competitive markets for both inputs and outputs; (iii) national aggregate output that can be explained by the amount of capital – particularly by aggregate value of the infrastructure - and the knowledge-base of the productive workforce; (iv) real wages equal to marginal productivities; (v) human capital (education, skills, and health of the workforce) as a major driving force of economic growth; (vi) inputs other than capital and labor were less important; and (vii) technological progress was Hicks neutral.

Solow concluded that technological change was a source of economic growth in the United States. Specifically, he reiterated, "gross output per man-hour doubled over the 1909 to 1949 period with 8.5% of the increase attributable to technical change". Notice that assumptions (i), (ii), and (iv) establish the conditions for the application of Cobb-Douglas functional form and for the use of Euler's theorem.

Under these presumed conditions, Solow specified his "special case of neutral technical change" to be estimated from an aggregate (macroeconomic) production function as follows[5]:

$$Q = A(t)f(K,L) \qquad (2.5)$$

where Q is aggregate output of the economy (i.e., the GDP); K is productive capital stock; L is the number of people in the workforce; A(t) is a measure of the "cumulative effects of shifts over time".

According to the formulation in Eqn. (2.5)[6], the Hicksian parameter, A, provides estimated measure of the shift in the production function at given levels of K and L. In effect, it is expected to capture "technical change", which is any

[5] Solow (1957), Romer (1996), Jones (1998), Hulten (2001), and Link and Segel (2003) are the main references for this section.

[6] Other formulations are: (i) $F\left[K_t,\left(A_tL_t\right)\right]$, which is referred to as "labor augmenting" or "Harrod-neutral"; and (ii) $F\left[\left(A_tK_t\right),L_t\right]$, which is referred to as "capital augmenting" or "Solow-neutral" (Jones 1998).

kind of shift in the production function: "slowdowns, speed ups, improvements in education of the labor force, and all sorts of things will appear as technical change" (Solow 1957). The aggregate production function model in Eqn. (2.5) has two important features. Firstly, time is not directly involved in the production function. This means that output changes over time only if the inputs into production change. If output rises under given quantities of K and L, then it can be inferred that there was disembodied technological progress. It means an increase in output realized through industrial restructuring, not through increases in inputs' quality and quantity, while embodied technological progress refers to increases in output realized through improvements in the quality of inputs – particularly labor and capital (Intriligator 1965; You 1976, Romer 1990, and Hulten 1992).

According to Solow's theory, the Hicksian parameter, A_t, which is the Solow residual TFP, is estimated using a nonparametric index number. This approach does not impose any restriction on the production function. Totally differentiating a logarithmic form of Eqn. (2.5) with respect to time and making simple algebraic arrangements yields the result expressed in Eqn. (2.6):

$$\frac{\partial Q/\partial t}{Q_t}=\left(\frac{\partial Q}{\partial K}\bullet\frac{K_t}{Q_t}\right)\frac{\partial K/\partial t}{K_t}+\left(\frac{\partial Q}{\partial L}\bullet\frac{L_t}{Q_t}\right)\frac{\partial L/\partial t}{L_t}+\frac{\partial A/\partial t}{A_t}$$

$$\frac{\dot{Q}}{Q_t}=\varepsilon_{QK}\frac{\dot{K}}{K_t}+\varepsilon_{QL}\frac{\dot{L}}{L_t}+\frac{\dot{A}}{A_t} \qquad (2.6)$$

Thus,

$$\frac{\dot{A}}{A_t} = \frac{\dot{Q}}{Q_t} - \left(\varepsilon_{QK} \frac{\dot{K}}{K_t} + \varepsilon_{QL} \frac{\dot{L}}{L_t} \right) \tag{2.7}$$

Eqn. (2.7) shows that the growth rate of the Hicksian efficiency index, *A*, is growth in real output minus the growth rates of capital and labor, both weighted by their respective output elasticities , ε_{Qi} (i = K, L). Note that the growth in real output indicates movement along the production frontier, whereas the growth rate of the Hicksian efficiency index, which is the so-called Solow residual, indicates a vertical shift in the production frontier.

In this nonparametric formulation, the output elasticities with respect to K and L are not observable. However, since Solow's model is based on the necessary condition for producer equilibrium in perfectly competitive markets for inputs and outputs, real wage is equal to the marginal productivity of a given input. That is,

$$\frac{\partial Q_t}{\partial K_t} \equiv MPK_t \equiv \frac{W_{CK_t}}{P_t} = W_{Kt}\text{; and } \frac{\partial Q_t}{\partial L_t} \equiv MPL_t \equiv \frac{W_{CL_t}}{P_t} = W_{Lt} \tag{2.8}$$

where W_{CLt} and W_{CKt} are current dollar prices of labor and capital, respectively, while W_{Lt} and W_{Kt} are their real dollar values; P_t is output price; and the subscript, t, is an index of a specific year. Then, substituting W_{Lt} and W_{Kt} for $\frac{\partial Q}{\partial L}$ and $\frac{\partial Q}{\partial K}$, in the parentheses of Eqn. (2.6), yields:

(a) $S_{Lt} = \frac{W_L L_t}{Q_t}$, share of labor in total-real value of output; and (b) $S_{Kt} = \frac{W_K K_t}{Q_t}$, share of capital in total-real value of output. Hence, again from Eqn. (2.7), the Solow residual, SR_t, can be calculated as follows:

$$TFP = \frac{\dot{A}}{A_t} \equiv SR_t = \frac{\dot{Q}}{Q_t} - \left(S_{Kt} \bullet \frac{\dot{K}}{K_t} + S_{Lt} \bullet \frac{\dot{L}}{L_t} \right) \qquad (2.9)$$

Eqn. (2.9) shows that the Solow residual TFP is output growth net of the sum of inputs weighted by their respective shares in total-real output value. This means TFP, in index number form, can be computed from prices and quantities.

SR_t is equivalent to the growth rate of the Hicksian efficiency index, A. But, for lack of theoretical foundations, different researchers give it different meanings. For example, Mawson et al. (2003) state that SR_t measures "free lunches associated with technological progress", while Hulten (2001) calls it something that is "a measure of our ignorance". In an extensive survey of the literature, Lipsey and Carlaw (2004) identify three "main positions" of groups of researchers who interpret the residual TFP differently as something that measures: (i) the rate of technological change; (ii) only the "free lunches" or "Manna from Heaven"; (iii) something useful, with no specific name; and (iv) "supernormal returns to investing in such changes – returns that exceed the full opportunity cost of the activity" (Carlaw and Lipsey 2003; Lipsey and Carlaw 2004; Lipsey et al. 2005).

To make the exposition clearer, a specific functional form is handy. After he experimented with various formulations, Solow (1957) used the following generalized Cobb-Douglas functional form to draw conclusions:

$$Q = A(t)K^{\alpha}L^{\beta} \tag{2.10}$$

where, assuming perfectly competitive markets for inputs and outputs and constant returns to scale, and where α and β ($\alpha+\beta = 1$) are shares in real total output value distributed to capital and labor, respectively. Furthermore, notice that α and β are elasticities of output with respect to capital and labor, respectively.

From Eqn. (2.10) the impact of technological progress on output can be estimated as a residual growth rate of TFP by taking the natural logarithm of that equation to formulate the following linear regression model with a stochastic disturbance term, ε:

$$\ln Q_t = \ln A(t) + \alpha \ln K_t + \beta \ln L_t + \varepsilon_t \tag{2.11}$$

Notice that the Cobb-Douglas production function in Eqn. (2.10) has unique features, which characterize it as a restrictive formulation. That is, (i) technological change is simultaneously Hicks-neutral, Harrod-neutral, and Solow-neutral; and (ii) the elasticity of input substitution, σ_{LK}, is unity. Thus, a general specification of the production function that permits flexible substitution of inputs, similar to the one in Eqn. (2.12), is necessary (Link and Siegel 2003):

$$Q = F\left(K, L, t\right) = G\left[a(t)K, b(t)L\right] \tag{2.12}$$

The generalized specification in Eqn. (2.12) provides Hicks-neutrality, if *a(t)* = *b(t)*, which means technological change is equally capital- and labor-augmenting; Harrod-neutral, if a(t) = 1, implying technological change is only labor-augmenting; Solow-neutral, if b(t) = 1, implying technological change is capital augmenting.

In closing, highlighting the pitfalls of maintaining all Solow's (1957) assumptions in the measurement of technological progress and growth accounting is in order. Arguments in the extensive literature (e.g., Nadiri 1970; Boskin and Lau 1992; Prescott 1998; Hulten 2001; Lipsey and Carlaw 2004) question particularly the validity of the restrictive assumptions of (i) constant returns to scale; (ii) neutrality of technological progress; and (iii) profit maximization, with perfectly competitive output and input markets. The following is a summary of the arguments:

Firstly, for an economy in which aggregate real output and inputs are all growing over time, it is difficult to identify separately the effects of returns to scale and technological progress. It is possible either one can be used as a substitute explanation for the other. Thus, given the likelihood of increasing returns to scale, maintaining the hypothesis of constant returns to scale would result in an overestimate of technological progress. Conversely, with the likelihood of decreasing returns to scale, maintaining that hypothesis would result in an under-estimate of technological progress. Moreover, if there are increasing returns to scale, the assumption of constant returns to scale implies that the sum of output elasticities with respect to the inputs is underestimated; and hence, at least one, if not both elasticities, is underestimated, implying that the rate of technological progress is overestimated. An additional implication is that the contributions of capital and labor inputs to economic growth will also be underestimated. The reverse would be true, if there are decreasing returns to scale. Examining equations (2.7) and (2.9) should make these arguments clear.

Secondly, if technological progress is non-neutral, then the rate of technological progress at time t will vary depending on the quantities of capital and labor inputs at time t. Most importantly, technological progress over many periods cannot be expressed simply as a smoothly cumulative sum of the technological progress that has occurred over the individual periods, nor can it be expressed simply as an average.

Thirdly, the assumption of profit maximization (or cost minimization), with competitive output and input markets, implies the equality of the elasticities of output with respect to capital and labor with their respective shares in total-real output value. However, given the possibilities of market and nonmarket constraints to instantaneous adjustments of inputs to their desired levels, the output elasticities with respect to each input are likely to deviate from a given input's share in the real-total output value. Hence, an estimate of technological progress obtained from Eqn. (2.9) will be subject to factor biases.

Furthermore, the estimated contributions of capital and labor inputs to economic growth will be subject to biases. For example, if the output market is monopolistic, then the input shares are likely to underestimate the output elasticities, causing in turn an over-estimate of technological progress, if equation (2.9) is used. The reverse is likely to be true in a monopsonistic market.

To avoid all these problems, therefore, direct estimation of an econometric model, such as that in Eqn. (2.11), is believed to be the best method. This is because such econometric models do not require imposition of the assumed restrictions as part of the maintained hypothesis in Solow's model (Boskin and Lau 1992).

Thus, given the fact that TFP growth is one of the major engines of economic growth, the *crux* of the challenges lies in how to measure, analyze, and interpret it. As the following sections show, the solution calls for an ongoing research with a joint implementation of the nonparametric and parametric approaches.

2.3 THE QUEST FOR A MEANING OF THE SOLOW RESIDUAL

The economic importance of TFP is well established. It is believed to be an engine of economic growth. It is the cause and the consequence of the evolution of dynamic forces that keep a given economy in motion (Nadiri 1970). The forces include technological progress, quality of human and physical capital accumulated over time, labor and management relations, and national and international institutional arrangements. But, the debate on the exact meaning of the Solow residual TFP and the techniques for measuring it continues.

The debate starts with a search for the correct definition of A_t: What is TFP? What are its determinants? What are the scientific techniques for measuring and analyzing it? As a start, assessing three general criticisms in the literature directed at the validity of the key assumptions of Solow's (1957) aggregate production function model is helpful.

Firstly, if the aggregate production technology is restricted to be constant returns to scale, i.e., a Cobb-Douglas form; and if each K and L is paid its respective marginal productivity, then, by Euler's theorem, the value of output equals the sum of the payment to the inputs. This means the sum of the shares of labor and capital in the total-real value of output in a given year, t, equals to unity. Thus, there is nothing in the derivation steps in equations (2.5) to (2.9) that requires constant returns to scale (Hulten 2001). In fact, Jorgenson and Griliches (1967) demonstrate that the condition for constant returns to scale is needed only to estimate, if there is any residual left as a return to capital.

Secondly, the marginal cost pricing, i.e., the marginal productivity condition in Eqn. (2.8), rules out the likelihood of imperfect market competition (or monopolistic competition), which leads to a price greater than marginal cost. Under this market imperfection, Hulten (2001) argues that the Solow residual was found to be a biased estimate of the Hicksian shift parameter, A_t, and "there is no way out of this problem" within the Solow index approach.

Thirdly, the Hicksian formulation in Eqn. (2.5) is valid only if inventions and/or innovations improved the marginal productivity of all the inputs at an equal rate. This is very strong assumption that is bound to lead to a biased estimate of A_t.

In an attempt to solve the problems associated with the Solow formulation, Hulten (2001) using the following more general formulation that allows improvements in technology to augment the marginal productivity of each input independently:

$$Q_t = F(\alpha_t K_t, \beta_t L_t) \tag{2.13}$$

Link and Siegel (2003), who specified the formulation in Eqn. (2.12), supported Hulten's (2001) formulation, which is specified in Eqn. (2.13). It is factor augmentation production technology, replacing the Hicksian parameter, A_t, with two augmentation parameters: α and β. Then, retaining all the other assumptions of Solow, except the constant returns to scale, the residual can be expressed as:

$$\begin{aligned} SR_t &= S_{Kt}\left(\frac{\partial\alpha/\partial t}{\alpha_t}\right) + S_{Lt}\left(\frac{\partial\beta/\partial t}{\beta_t}\right) \\ &= S_{Kt}\left(\frac{\dot{\alpha}}{\alpha_t}\right) + S_{Lt}\left(\frac{\dot{\beta}}{\beta_t}\right) \end{aligned} \tag{2.14}$$

Thus, SR_t, the Solow residual, is now the output-value share weighted average of growth rates of the input augmenting parameters; and still it measures changes in TFP.

However, the intellectual "debate", "criticism", and/or "concern", does not end here. In general terms, Domar (1961) argued against previous studies, which concluded that "80-90% of output growth per unit of labor in the United States" was attributable to technological progress, measured in terms of the SR_t, "the remaining 10-20% being all that capital (and land) could claim". Domar argues that the SR_t, "which does not even have a scientific name and theory behind it", does not take into account contributions of all inputs and attributes that characterize a production technology.

That is, it does not value effects of several technological attributes, such as economies of scale and scope; enhanced quality of the workforce acquired through improved health, education, and skills of the labor force; effective and efficient management; and changes in product mix. Moreover, "the heavy weight" assigned to the contributions of labor productivity in macroeconomic models is misleading, because partial productivity of labor (PPL) is a function of all inputs[7].

In addition, the various names given to SR_t by different researchers appear to add more confusion. For example, Domar (1961) identifies the following six names used by different researchers: "output per unit of input", "efficiency index", "total factor productivity", "change in productive efficiency", "technical change", and " a measure of our ignorance".

Furthermore, in the very recent literature, pioneered by Richard G. Lipsey and associates, TFP is described as a measure of "supernormal gains", associated with investments in R&D (Carlaw and Lipsey 2003; Lipsey and Carlaw 2004; Lipsey et al. 2005). These authors interpret the "supernormal gains" as gains that are over and above the opportunity costs of expenditures made mainly in R&D.

In sum, the quest for a universally accepted interpretation of TFP goes on. For the purpose of this study, however, TFP growth is an indicator of output growth realized through combined effects of production scale and technological

[7]This aspect is explored fully in Section 3.2 (Chapter 3).

progress. These two mutually reinforcing effects cause a vertical shift in the frontier of the production technology.

2.4 THE NEED FOR JOINT IMPLEMENTATION OF THE TWO METHODS

The steadily growing literature shows that joint implementation of the nonparametric and parametric methods can "dispel our ignorance" (e.g., Domar 1961; Griliches and Jorgenson 1967; Hulten 2001; Carlaw and Lipsey 2004; Lipsey et al. 2005). As Hulten (2001) puts it, "both approaches can be implemented simultaneously, thereby exploiting the relative simplicity and transparency of the nonparametric estimates to serve as bench-marks for interpreting the more complicated results of the parametric approach".

The intuition is that empirical results from both the nonparametric and parametric methods can illustrate "the dichotomy between the shift in the production function and the factor-driven movement along the function" (Hulten 2001). Thus, the justification for joint implementation of the two methods is based on the strengths and limitations of each method. The nonparametric method has the following merits: (i) it allows multiregional and international comparisons; (ii) enables measurement of growth rates and levels of productivity; (iii) is easily understood by policy makers, business executives, and other non-specialists; (iv) avoids the problems often associated with specification and estimation of econometric models; (v) displays results that reveal data anomalies, unlike statistical approaches that tend to conceal irregularities; and (vi) enables the researcher to examine efficiency in terms of a wide range of measures, such as historical trends and cycles in the data and the productivity indices (Freeman et al. 1987; Frank et al. 1990; Ghebremichael et al. 1990; Ghebremichael and Nanang 2004). The main drawback of this procedure is that it does not provide the several parametric measures of production technology and technological change that an econometric model does.

But, it is clear that an econometric method also has pitfalls. They include the challenges associated with (i) identifying all potentially "correct" explanatory variables in order to build credible model, starting with a correct specification of the production technology; (ii) choosing the right flexible functional form and estimation techniques; (iii) identifying, explaining, and diagnosing simultaneity problems[8]; and (iv) many other statistical challenges.

In summary, the resolution of that debate appears to rest on the joint implementation of both methods. Empirical work that combines these two methodologies is expected to explain "the measure of our ignorance" (Hulten 2001). It is also expected to address concerns of many researchers – particularly those of Jorgenson and Griliches (1967) - who argued that the residual ought to vanish if all explanatory variables are paid their respective marginal productivities; and that the aggregate measures of K and L inputs possess *embedded qualities* obtained from R&D expenditures.

Out of the extensive intellectual debate on how to model, measure, and analyze economic growth, a new growth theory, endogenous growth theory, is gaining some momentum in the academic world. The complex models of this

[8] For example, in a simple production function, K and L on the right hand side of a regression equation depend on the dependent variable, Q, the level of which is endogenously decided by management. Based on the level of Q, management decides what amounts of K and L should be used, leading to simultaneity problem.

theory focus mainly on how R&D contributes to TFP growth and thereby to economic growth. The theory is highlighted next.

2.5 ENDOGENOUS GROWTH THEORY

As pointed out above, the neoclassical exogenous growth theory assumes that effects of inventions and/or innovations are exogenously determined under given R&D expenditures. But, this is far from reality. A more realistic approach is to recognize that R&D makes significant contributions to the growth of TFP endogenously (e.g., Romer 1986, 1990; Hulten 1992; Jones 1995a, b; Jones 1998; Griliches 1998; Aghion and Howitt 1999; Hulten 2001). It is instructive to observe that these and other researchers use more or less similar specifications of endogenous growth models to explain implications of *endogeneity* of technological progress for the measurement and interpretation of TFP.

For example, Hulten (2001) specifies the following variant of the generalized Cobb-Douglas functional form of the production function to illustrate the workings of the endogenous growth model:

$$Q_t = A_0 K_t^{\alpha} \left(K_t^{\beta} L_t^{\gamma} \right) \quad \alpha + \beta = 1; \quad \beta + \gamma = 1 \qquad (2.14)$$

According to the formulation in Eqn. (2.14), capital, K, has two effects: (i) a one percent increase in K raises output of its owner-user by a percent; and (ii) a spillover effect on the output of other users. Furthermore, observe that $\alpha + \beta = 1$, implying constant returns to scale in the K variable across all producers; and $\beta + \gamma = 1$ implies K and L are also subject to constant returns to scale. In addition, this formulation exhibits increasing returns to scale. However, it is consistent with competitive equilibrium, because each producer operates under the assumption of constant returns to the inputs that the producer monitors and controls.

But, what does the new formulation in Eqn. (2.14) imply for the residual TFP, computed from the formulation in Eqn. (2.9)? Notice that the residual is derived from the Hicksian production function formulation in Eqn. (2.5), while the formulation in Eqn. (2.14) is a special case of that function in which the output elasticities are constant (Cob-Douglas) and the efficiency term, $A_0 K_t^{\alpha}$, replaces the Hicksian efficiency parameter, A_t.

The associated residual, like that in Eqn. (2.9), is equal to the growth rate of capital weighted by the spillover effect. The analogous TFP residual continues to measure costless gains to society – the "Manna from heaven" – realized through innovations (Hulten 2001). But, the "Manna" is associated with the externality parameter, α, instead of the Hicksian efficiency parameter, A_t. According to the New Growth theory, therefore, the approach to estimating the residual is not a nonparametric approach. It is a parametric approach, which is a reflection of a given process.

In short, the new endogenous growth theory supports the following five economic policy prescriptions: (i) that government policies that stimulate competitiveness in the marketplace result in economic growth; (ii) that there are potential increasing returns from higher levels of capital *deepening*[9]; (iii) that private investment in R&D is the central source of technological progress; (iv) fully specified and protected property rights and patents can provide the incentive to engage in R&D; and (v) that investment in human capital (education and training of the workforce) is a necessary ingredient of economic growth.

2.6 IMPERATIVES OF EFFECTIVE INSTITUTIONAL ARRANGEMENTS

Arguing on the importance of institutional arrangements for productivity measurement and analysis, the Nobel Prize Laureate, Douglass C. North (1993), criticizes the "biased tendency of neoclassical economists". He reiterates that institutions, which are "the rules of the game of an economy", play determinant roles in the process of productivity growth and, hence, national wealth. He makes his point as follows:

> …….. …..that institutions matter ….and that they must be integrated with classic sources of productivity change if we are to understand the long-run and for that matter short-run performance of economies.

Consisting of "formal rules, informal constraints (norms of behavior, conventions, and self imposed codes of conduct), the enforcement characteristics that humans impose on their dealings with each other, institutions are "the humanly devised constraints on human interaction" (Noth 1993). Institutions are "constructs of the human mind" that cannot be seen, felt, or

---

[9] **Capital deepening** is the process of capital stock accumulation at a faster rate than the growth rate of the labor force, while **capital widening** is the process of accumulating capital stock at the same rate as the growth rate of the labor force so that the capital labor ratio remains constant (Pearce 1992).

measured (North 2002). In effect, without effective institutions, public and private policies cannot be implemented effectively and efficiently.

Recent and extensive literature shows that effective institutional arrangements, enhanced investments in R&D, and technological progress are the main sources of productivity and thereby economic growth (e.g., Romer 1990; North 1993; Lipsey et al. 2005). Technological progress is realized through intentionally planned investments made by profit maximizing private firms. But, if a given technology is patent free, it is nonrivalrous and nonexcludable. This is particularly important when one takes into account the quality of human capital, the embodied knowledge base.

Economic theory suggests that the existence of nonconvexity, due to nonrivalriness and nonexcludability, perfectly competitive market structure for technology (knowledge) cannot be supported. This by itself calls for effective arrangements of relevant institutions for intellectual property rights. Romer (1990) developed his model under the following three premises to argue against the conditions under which the aggregate production function-based economic growth model of Solow (19957) was expected to work: Firstly, he concurred that technological progress is an engine of economic growth. Secondly, technological progress arises because rent seeking (profit maximizing) economic agents that respond to market incentives make decisions to invest in R&D and other opportune areas that result in endogenous *technological progress*. Thirdly, marginal costs for innovative techniques (i.e., innovations) are zero: once they are created they can be used over and over free of any marginal cost (e.g., computer software). Romer (1990) draws the following three conclusions: that the stock of human capital determines the rate of economic growth; that integration into world markets would increase growth rates; and that having a large population was not sufficient to generate growth, as the Solow model implies.

In Canada, activities of firms, trade unions, and other socioeconomic organizations are constrained by federal and/or provincial institutional arrangements. Specifically, the institutional arrangements that govern sustainable forest ecosystem management deal with complex issues whose effects can be examined within the framework of the forestland tenure system. This system stipulates that 93% of Canada's forest resources are publicly owned, while private woodlot owners manage the remaining 7% (The Canadian Forest Service 2006b).

The Canadian Constitution enunciates that the federal, provincial, and territorial governments have specific roles in sustainable management of forest ecosystems. The 10 provinces and three territories have legislative jurisdictional authority over the conservation and sustainable management of 77%, while 16% is under the federal government's purview. About 80% of total timber harvesting by private companies takes place in the publicly owned forests (The Canadian Forest Service 2006b). Institutional arrangements on timber harvesting contracts made between provincial/territorial governments and companies place legally binding obligations on the companies to pay harvesting fees, and to submit plans that ensure sustainable forest management in return for the right to harvest timber. The management plans must be submitted to government authorities for approval before the start of harvesting operations.

Frequent changes in institutional arrangements of the contracts occur in the Canadian forest policy, because of conflicting interests of three bodies: the governments that attempt to obtain maximum economic rent of forest resources; the companies that seek to maximize profits; and the labor unions that aspire for secured jobs and fair wages.

Furthermore, due to the jurisdictional mandates, the national constitution on forest tenure system accords to the federal and provincial/territorial governments to develop a national forest policy regime. This varies often with provincial, territorial, and local community development goals and objectives. A variety of ideas and institutional arrangements on sustainable forest ecosystem emerge from a complex of interests of governments, industries, local communities, and labor unions.

For illustrative purposes, this study focuses on key fiscal policy institutional arrangements. Specifically, effects of changes in taxation policy instruments on capital formation and total factor productivity growth are analyzed [Section 5.3.2(B)].

2.7 THE THEORY OF PATH DEPENDENT TECHNOLOGICAL PROGRESS

Recent literature shows that the theory of path dependence plays an important role in the study of technological progress and economic growth (Ruttan 2001). Depending on the subject matter under review, path dependence is used to explain two concepts: “history matters”, a very broad and “trivial” conception which means "everything has causes" and institutions are self-reinforcing social constructs. This is a well focused concept with scientific explanatory power.

Reiterating the importance of historical facts that describe path dependence for evaluation of industrial performance, Rosegger (1986) states,

> "Performance evaluation does not deal in scenarios of what might have been, it deals with the "facts" of the past. What performance evaluation aims at is an understanding of the technological and economic factors, internal or external to the entity being evaluated, that caused observed changes in such variables as the productivity of inputs, costs, prices, and profits".

Generally, path dependence is used to explain general conceptions, such as (i) specific patterns of timing and sequence matter; (ii) starting from similar conditions, a wide range of social outcomes may be possible; (iii) large consequences may result from relatively "small" or contingent events; (iv) particular courses of action, once introduced, can be virtually impossible to reverse; and consequently, political development is often punctuated by critical moments or junctures that shape social life (Pierson 2000).

That is, if historical events affect long-run equilibrium patterns, an economic system is path-dependent. Big events, such as plagues, catastrophes, wars, and major inventions and/or innovations, affect the steady state of an economy (Bassanini 1997). It is clear that technological changes in the Canadian forest products sector are part of Canada's economic history. The Canadian economy evolved from one that was a natural resource dependent, exporter of primary products (e.g., lumber, fur, and fish), to its current position of a high-tech dominated economy. With no doubt, there are historical forces that drove this technological advancement. In effect, cumulativity and specificity of path dependent technological changes result in irreversibility and self-reinforcing mechanisms that amplify effects of historical events (Pierson 2000).

Moreover, TFP growth, considered as an upward vertical shift in the production frontier, is path dependent and several forces, such as technical change and capital deepening are considered to be always at work simultaneously (Givon 2006). Technological advance that occurs sequentially causes differences in measured TFP changes.

The challenge is in understanding and explaining those forces. Ruttan (1997) argues that induced innovation, evolutionary theory, and path dependence are sources of technological change. Evolutionary economic theory posits that technological change is driven by continual creation of technological variety through inventions, innovations, and diffusion processes. Generally it is conceptualized that dependence of current technology on past and existing knowledge tends to move firms, regions, and nations along well defined technological trajectories (Essletzbichler and Winther 1999).

In the forest products sector, historical records of major events, such as outbreak of wildfire, diseases, and endemic insects adversely affect timber supply, leading to changes in market demand and supply. Such events are incentives that stimulate search for all sorts of new technologies through R&D investments. Under these supply side shocks, research projects similar to this one would focus on enhancing productivity in timber harvesting and in sawmilling operations.

In short, there can be no doubt that technological change is path dependent. It can be driven by either supply side or demand side forces or by a combination of both. The key to the concept is time path: "technological change evolves from earlier technological developments" (Ruttan 1997). On the importance of the theory of path dependence, Hirsch and Gillespie (2001) make the following convincing argument:

> Path dependence deserves credit for bringing history back into analysis of economic and technological development, stimulating economists and other social scientists to address the limitations of their largely *ahistorical* models. Path dependence points out the paradox of researchers using history as a data bank and source of economic variance, even while simultaneously assuming that history does not fundamentally differ from, and has no implications for, the present.

Thus, this study, which covers a forty-year period (1961-2000), places the dynamics of the key technological attributes that characterize the Canadian sawmilling industry's production technology into their historical perspectives. Particularly, the historical trends in gross TFP have reflected path dependence of technical improvements and technological progress.

2.8 THEORETICAL UNDERPINNINGS OF SELECTED STUDIES

In this section, selected studies whose theoretical underpinnings contributed significantly to the processes of building the empirical models used in this study, are highlighted. In analyzing dynamics of technological attributes in an industry, computation of real capital stock and its rental price is the most challenging part. Rental price of capital depends on accurate measurement of its real capital stock, the asset market price, the rate of return, the rate of replacement, and the tax structure of a given economy. In a seminal paper, Christensen and Jorgenson (1969) pioneered a technique called perpetual inventory procedure for establishing aggregate *quantity* and *price* indices of various vintages of capital. This method has become a standard tool used by public and private organizations. For example, in its ongoing program of database building for capital stock in current and constant dollar values, Statistics Canada (2001) uses the perpetual inventory method, with which it is possible to calculate *rental price* and to adjust stocks and prices for relative utilization of capital[10].

Productivity change is both the cause and consequence of the evolution of dynamic forces operative in an economy – technical progress, accumulation of human and physical capital, enterprise, and institutional arrangements (Nadiri 1970). Measurement and interpretation of its dynamic behavior at the microeconomic and macroeconomic levels require the understanding of many complex factors. In its partial factor productivity (PFP) and total factor productivity (TFP) forms, productivity is the main measure of technological progress (Kennedy and Thirlwall 1972). Regarding methodologies of measuring and analyzing productivity parametrically, Kennedy and Thirlwall (1972) caution about the drawbacks of the Cobb-Douglas form, which has restrictive assumptions of: (i) neutral technological progress; (ii) unitary elasticity of factor substitution; (iii) constant returns to scale; and (iv) disembodied technological progress, as in the case of Solow's growth model.

The challenges of formulating an effective econometric functional form and aggregation lie at the heart of applied production economics (Chambers 1988). Christensen et al. (1973) developed the transcendental (TL) logarithmic

[10] The math of this procedure is summarized in Section 4.2 (Chapter 4).

production and price possibility frontiers. These frontier functional formulations are quadratic in the logarithms of the quantities of inputs and outputs. Christensen et al (1973) demonstrate that the TL frontiers provide accurate global approximations for many of the production and price frontiers used in econometric studies of production[11].

Christensen (1975) challenged those who used partial factor productivity (PFP) for decision-making. He stated, "Thus, I do not believe that I have to convince this audience of the importance of total factor productivity concept" (TFP). With that assertion, Christensen derived and explained various conceptual index number approaches to the measurement and analysis of TFP.

Christensen et al. (1980) conducted a comprehensive international comparison of economic growth over the period of 1947-73. The study covered nine countries: Canada, France, Germany, Italy, Japan, Korea, the Netherlands, the United Kingdom, and the United States. The primary objective of the study was to separate growth in real input from growth in TFP in order to account for growth in real product for each country. The production technology was assumed to be characterized by constant returns to scale; and was specified as a function of capital, labor, and a time-trend variable only. The authors concluded that variations in aggregate economic growth for the period 1960-73 were associated with variations in the growth of real input; and that the rapid growth in real product was associated with rapid growth of both real capital input and real labor input.

---

[11] More explanations on the effectiveness of the TL form of the dual cost function are given in sub-section 3.3.3 (Chapter 3: Methods).

Applying the Tornqvist index procedure, Christensen and Cummings (1981) analyzed real product, real input, and productivity in the economy of the Republic of Korea for the period of 1960-73. Their findings revealed that the average annual growth rates of real output, real input, and TFP were 9.7%, 5.5%, and 4.1%, respectively.

Berndt and Watkins (1981) carried out a rigorous analysis of energy prices and productivity trends in the Canadian manufacturing sector for the period of 1957-76. They estimated a long-run TL cost function; and found that capital was substitutable for labor and energy; and that labor and energy were substitutes for each other. However, they cautioned that the aggregated nature of the data made their findings less credible.

Rao and Preston (1983) analyzed the causes of inter-temporal variations in factor intensities and TFP in major Canadian industry groups, such as agriculture, forestry, mining, and the manufacturing sector. The authors estimated a TL form total cost function; and found out that many of the industries experienced 15 to 20 percent slowdown in TFP growth after 1973.

As discussed in Section 2.2, Solow's (1957) pioneering work associates technological progress, i.e., TFP growth, with time derivative of an aggregate production function. Although a useful conceptualization, Solow's formulation is not appropriate for actual measurement and analysis of productivity (Caves et al. 1982b). Since index number procedures entail comparisons of discrete points in time, using discrete data points, the procedures require a discrete approximation to continuous time derivative. Caves et al. (1982a) demonstrated that "superlative index" numbers could be used for making multilateral comparisons. By permitting the first order TL parameters to differ across economic entities, the authors developed "superlative" output and input indices; and formulated a TL multilateral productivity index. Continuing with refinement of their work, Caves et al. (1982b) developed an index number construction procedure for making comparisons under very restrictive general circumstances. Malmquist input, output, and productivity comparisons were defined for structures of production with arbitrary returns to scale, substitution possibilities, and biases in productivity change. For TL production structures, Tornqvist output and input indices were shown to be equal to the mean of two Malmquist indices. The Tornqvist productivity index, corrected by a scale factor, was shown to be equal to the mean of two Malmquist productivity indices.

2.9 SUMMARY

To lay a strong foundation on which the empirical models for this study are built, the pertinent theoretical framework is detailed in the previous sections. That is, the challenges associated with economic growth theory in general and with the measurement, analysis, and interpretation of TFP in particular are detailed. This section summarizes that discussion and links it to the empirical methods, which are explained in Chapter 3.

What are the elements of TFP? Conversely, what does TFP measure? Conceptually, it is believed that the residual TFP captures changes in the amount of output that cannot be attributed to a given set of inputs. Intuitively, it measures vertical shift in the production frontier. But, many factors affect the shift. They include technical innovations, organizational and institutional changes, shifts in societal preferences, fluctuations in demand, changes in input shares in the total-real value of output, omitted variables, and measurement errors. Hence, the residual TFP cannot be interpreted as technological change (Hulten 2001; Carlaw and Lipsey 2003; Lipsey and Carlaw 2004; Lipsey et al. 2005).

To the extent that productivity is affected by the rate of inventions, innovations, and diffusions of new technologies, it is commonly accepted that TFP captures the costless part: "the Manna from Heaven" or "free lunch". It may measure the so called "supernormal gains"; and it may also reflect spillover externalities from R&D projects elsewhere and effects of enabling institutional arrangements, such as taxation policy instruments and well-defined property rights and patent rights.

Furthermore, the residual is a nonparametric index number designed to estimate one parameter in the larger structure of production, the efficiency shift parameter, A_t. It uses prices to estimate marginal products in order to accomplish this. Thus, the various factors comprising TFP are not measured directly, but are lumped together as a "left-over" factor (hence the name residual). They cannot be factored out within the pure TFP framework; and this is the source of the "famous epithet", as Hulten (2001) puts it, "a measure of our ignorance".

In addition, the Divisia index must be path independent to be unique. The discrete-time counterpart of the Divisia index, the Tornqvist approximation, is an exact index number, if the underlying production function has the TL form. The problem of path dependence is one of uniqueness, which is not the same thing as measurement bias.

The two conditions for path independence are the existence of an underlying production function, and marginal productivity pricing. Although they are usually assumed for convenience of measurement, neither constant returns to scale nor Hicksian neutrality are absolutely necessary conditions. It is only when the various assumptions are met that the residual is a valid measure of the shift in the production frontier. However, it generally understates the importance of productivity change in stimulating the growth of output, because the shift in the production frontier generally induces further movements along the function as capital increases.

Finally, the literature shows that the quest for the exact meaning and the theory of the residual TFP remains open. In Hulten's (2001) words:

> The residual is still, after more than forty years, the workhorse of empirical growth analysis. For all the residual flaws, real or imagined, many researchers have used it to gain valuable insights into the process of economic growth. Thousands of pages of research have been published, and more are added every year. Total factor productivity has become a closely watched government statistic. Not bad for a forty-year old.

In short, the positive value of the TFP residual outweighs the negatives. The residual has provided a simple and internally consistent intellectual framework for organizing data on industrial performance and economic growth; and has provided the theory to guide economic measurement (Hulten 2001).

Despite the lack of universally accepted theory behind it, the residual TFP is the best available yardstick to measure and analyze performance of a given economic entity, such as a firm and an industry. For instance, a complete picture of the industrial dynamics of an economy would require correctly measured and analyzed TFP residuals. In addition, whatever limitations a TFP model has are equally applicable to any other model, be it an econometric or any other empirical model. This challenge, therefore, calls for joint implementation of the nonparametric and parametric methods, as done in this study.

CHAPTER 3 METHODS

Chapter 2 has established the ground for building the two empirical methods. Sufficient justifications of the need for joint implementation of the nonparametric and the parametric (econometric) approaches to analyze industrial technologies are presented in that chapter. Here, the two methods used in this study are described. First, the production technology of the Canadian sawmilling industry is specified in Section 3.1, while the importance and concepts of productivity are highlighted in Section 3.2. Then, the workings of the two empirical methods: (i) the nonparametric method, which involves application of the multilateral index model and (ii) the econometric method, which involves estimation of a long-run dual-cost function, are described in sections 3.3 and 3.4, respectively.

3.1 THE PRODUCTION TECHNOLOGY

Microeconomic theory of production deals with the process of combining and coordinating productive resources and services, which are collectively called inputs. What to produce, how much to produce, and the optimal combination of all inputs are the key issues in any production process. These issues are of concern to an industry as well as to a society. Hence, a production function can be defined as a mathematical specification of the various technical production possibilities a firm faces. For given levels of inputs, a production function is expected to represent the maximum output(s) in physical terms.

In general, the concern of production economics is not only choice of effective and efficient techniques of production, but also how choices are influenced by changes in *technology*. Mathematical specification of the production function can range from simple algebraic functions, such as a function relating corn yield to fertilizer dosage, to highly complex systems of equations, such as a detailed model of corn plant growth and response to nitrogen fertilization (Beattie and Taylor 1985). The degree of mathematical complexity of the production function depends on the complexity and scale of the production process and the degree of the desired accuracy. But, cost and manageability of the research must be taken into account. In most cases, cost effectiveness determines the socioeconomic and scientific merits of a research project.

For the purpose of this study, the following production function was assumed to explain the production technology of the Canadian sawmilling industry:

$$Q_t = f(K_t, L_t, E_t, M_t; T_t) \tag{3.1}$$

where Q = aggregate of the three types of output: (i) lumber, (ii) shakes and shingles, and (iii) all marketable sawmilling operations' byproducts that include wood chips, sawdust, slabs, edgings, and shavings, which are sold to pulp mills; K, L, E, and M are capital, labor, energy, and sawlogs, which are the sole raw material input, respectively; T is a time trend variable, which is expected to capture *disembodied* technological progress, measured by TFP (Solow 1957; Berndt and Watkins 1981; Chambers 1988; Griliches 1998; Diwan and Chakraborty 1991); and the subscript t stands for a specific year during the study period.

The trend variable, T, is a poor indicator of technological change, because it is used under the presumption that technological progress is *smooth* and *steady*. If the goal is to obtain an exact measure *of* technological dynamics, this problem is quite serious. But, if the goal is to test for the existence of technological change and statistical significance of its impact on production cost, this approach is valid (Nautiyal and Singh 1985). Furthermore, Chambers (1988) argues for the validity of using T as follows:

> "This approach is sometimes disparaged as being a measure of our ignorance than anything else. But, even if it is true, should one be upset at being able to measure one's ignorance?"

Hence, in this study, T is expected to provide information on the presence of technological progress over the forty-year study period. Previous studies, which are all of the 1980s, used the specification in Eqn. (3.1) (e.g., Singh and Nautiyal 1985; Nautiyal and Singh 1985; Martinello 1985; and Meil and Nautiyal 1988).

3.2 NONPARAMETRIC METHOD OF PRODUCTIVITY ANALYSIS

3.2.1 Importance and Concepts

A. Importance

> The importance of productivity for the future growth of living standards, defined as GDP per capita, is becoming increasingly recognized. ...Productivity growth really is our economic destiny. But, the Achilles heel of Canadian economic performance in recent years has been weak productivity growth, a disconcerting development (Sharpe 2006)[12]

In general terms, productivity is the core of the science of economics. Although the Solow residual, detailed earlier, is accepted as a measure of the

[12] Presentation of Andrew Sharpe, Executive Director, Centre for the Study of Living Standards, to the panel session on "Human Capital, Technology, and Innovation" at the Conference on Canada's Competitiveness and Prosperity, organized by the Institute for Competitiveness and Prosperity, Ottawa, Ontario, March 10, 2006.

shift in the frontier of production technology, it does not explain the importance of productivity improvement as a source of economic growth. Researchers attribute part of the historically observed growth rate of capital stock (i.e., steady increases in capital formation) to productivity growth.

In its broadest sense, however, productivity is the amount of aggregate output per unit of aggregate quantity of inputs. Enhanced productivity is an indicator of *efficient* and *effective* utilization of scarce economic resources (e.g., labor, various vintages of capital, and natural resources) to generate goods and services.

In summary, there are multiple direct and indirect (spin-off) benefits that society gains from improvements in industrial productivity. They include the following: (i) mitigation of accelerated depletion of natural resources; (ii) minimizing environmental damages caused by industrial operations; (iii) saving in the use of the productive services of scarce economic resources, i.e., minimizing consumption of a given input per unit of output; (iv) minimizing impacts of inflation on performance of a given economy by off-setting rising wage-rates and other input prices; and (v) improvement in the competitiveness of national industries in the global marketplace. Consequently, public policy makers and industry executives pay special attention to strategies that lead to productivity improvement (Sharpe 2006).

In addition, the growing number of national and international productivity research centers shows the importance of productivity growth for social welfare improvement. Examples of national and international centers include the

European Association of National Productivity Centers, the Asian Productivity Association, the American Productivity Association, and the Japanese Productivity Association.

B. Concepts

While the computation techniques are discussed in the next section, the concepts and the challenges associated with measuring and analyzing productivity are briefly discussed here. As detailed in Chapter 2, whatever "label" is placed on it (e.g., "measure of our ignorance" or "Manna from Heaven"), TFP is considered as more illuminating indicator of technological progress than partial factor productivity (PFP), which is productivity of a single input (Ghebremichael and Nanang 2004).

As detailed in the previous chapter, an analysis of TFP is considered as economic growth accounting. This conception is based on the pioneering work of Solow (1956, 1957). TFP indices are used to measure the residual growth in output not accounted for by the growth in inputs. That is, TFP growth rate is defined as the rate of aggregate output growth minus the rate of aggregate input growth.

Many researchers are reluctant to calculate and report PFPs, because of the lack of credibility associated with them. However, an extensive literature reveals that business executives, policy makers, and academic researchers find trends in and levels of partial productivity of labor (PPL) of particular interest for various reasons (e.g., Solow 1957; Daly and Rao 1985; Gordon 1987; Frank et al. 1990; Ghebremichael et al. 1990; Ghebremichael and Nanang 2004). But, this is misleading, because aggregate productivity cannot be attributed to a single input, because production is a function of all inputs (Ghebremichael et al. 1990; Ghebremichael and Nanang 2004). If, for example, high partial productivity of energy (PPE) is observed, it can be due to either intensive use of labor, capital, or Material.

In short, PFP_i, partial factor productivity of input i, is a function of the inputs that constitute the production technology, as specified below:

$$PFP_{it} = f\left(K_t, L_t, E_t, M_t\right) \qquad (3.2)$$

Keeping in mind the above caveat, PFP of each of the four inputs and the TFP are analyzed in this study. Analyses of both types of productivity are based on the production technology specified in Eqn. (3.1). That is,

$$PFP_{it} = \frac{Q_t}{x_{it}} \qquad (3.3)$$

where PFP_{it} = partial factor productivity of input i (= K, L, E, M); Q_t = aggregate quantity of the three types of output specified for Eqn. (3.1); x_{it} = quantity input i; and the subscript t depicts a specific year during the study period.

In general terms, TFP is a measure of productivity of all inputs combined. It can be defined as a ratio of aggregate output, Q_t, to aggregate input, X_t:

$$TFP_t \equiv \frac{Q_t}{X_t} \qquad (3.4)$$

Depending on the structural characteristics of the production technology in question, TFP has the following three types of quantitative *measures* (Ghebremicahel et al 1990; Ghebremichael and Nanang 2004):

(1) In line with Solow's (1957) conception, if the production technology is characterized by constant returns to scale (CRTS), TFP is specified as a function of the technological change index term only. That is,

$$TFP_t = f(T_t) \tag{3.5}$$

(2) If the technology is homothetic, but does not produce at CRTS, then TFP is a function of both output and technological change[13]:

$$TFP = f(Q_t, T_t) \tag{3.6}$$

(3) While the above measures are used to assess a homothetic[14] production technology, TFP of a nonhomothetic technology is a function of all inputs and technological progress, which is expected to be captured by T:

$$TFP_t = f(K_t, L_t, E_t, M_t, T_t) \tag{3.7}$$

Although there is no universally accepted interpretation of the quantitative results of TFP, Chambers (1988) provides the following three interrelated interpretations: (i) average product of an aggregate input, as expressed in Eqn. (3.4); "(ii) a measure of the rate of technical change; and (iii) an index of input effectiveness in producing output before and after technical change, that is, if technical change makes the aggregate input more productive, the TFP index is greater than 1; if the aggregate input becomes less productive TFP is less than

---

[13] A homothetic function is a monotonic transformation of a homogeneous function. Hence, even functions that do not necessarily exhibit CRTS, such as the Cobb-Douglas and the CES functions, can have homothetic isoquant maps (Nicholson 2002).

[14] A production functions whose isoquants are parallel radials of each other is called *homothetic*. It is characterized by a constant marginal rate of technical substitution along any ray from the origin. Consequently, input-price ratio does not change under this condition of production equilibrium.

1; and in the absence of technical effects on the aggregate input, TFP is equal to 1" (Ghebremichael and Nanang 2004)..

Recall that the fundamental challenges in measuring, analyzing, and interpreting TFP are explained in Chapter 2. One of the major challenges is aggregation of various inputs and outputs accurately. For example, "one cannot obtain a meaningful measure of all inputs by simply adding number of workers, quantities or dollar values of fuels, Material, etc." (Ghebremichael et al. 1990; Ghebremichael and Nanang 2004). To overcome this difficulty, economists have devised methods of aggregating various quantities measured in different units into meaningful input and output indices. The procedure is discussed next.

3.2.2 The Multilateral Index Procedure

To evaluate methods and results of fourteen TFP studies conducted on the U.S. agricultural sector, Trueblood and Ruttan (1995) categorized the methods of those studies into three: index number, production function, and non-parametric (e.g., data envelopment analysis). They concluded "that many economists prefer the Divisia index", because it is believed to be "theoretically consistent with flexible production functions and avoids the problems associated with estimating those functions" (Ghebremichael and Nanang 2004).

However, the Divisia index cannot be used for discrete (annual) data, because it is based on the following three impracticable presumed conditions: that a continuously twice-differentiable production function characterized by an instantaneous growth process exists; that the production function is homogeneous of degree one; and that each input is paid its marginal productivity

(Star and Hall 1976). Since economic data are observed in discrete time quantities, some form of approximation is needed.

Christensen and Jorgensen (1969) derived a procedure known as the multilateral index procedure, which is the Tornqvist discrete time approximation to the Divisia index procedure. Caves et al. (1982a,b) refined the work of Christensen and Jorgenson (1969) to the following formulation:

$$\frac{TFP_t}{TFP_s} = \exp\left[\frac{1}{2}\sum_{i=1}^{3}\left(S_{Rit}+\bar{S}_{Ri}\right)\left(\ln Q_{it}-\tilde{Q}_i\right)-\frac{1}{2}\sum_{i=1}^{3}\left(S_{Ris}+\bar{S}_{Ri}\right)\left(\ln Q_{is}-\tilde{Q}_i\right)\right]$$
$$-\exp\left[\frac{1}{2}\sum_{j=1}^{4}\left(S_{Cjt}+\bar{S}_{Cj}\right)\left(\ln X_{jt}-\tilde{X}_j\right)-\frac{1}{2}\sum_{j=1}^{4}\left(S_{Cjs}+\bar{S}_{Cj}\right)\left(\ln X_{js}-\tilde{X}_j\right)\right] \tag{3.8}$$

where Q_i = aggregate quantity of outputs, *i* = 1, 2, 3 [i.e., lumber, shakes and shingles, and all of the industry's tradable by-products), as described under Eqn. (3.1); X_j = aggregate quantity of the inputs, *j* = 1, 2, 3, 4 (i.e., K, L, E, M]; S_{Ri} = share of output *i* in total revenue over the entire sample; S_{Cj} = share of input *j* in total cost over the entire sample; $\bar{S}_{Ri}$ = an arithmetic mean value of the share of output *i* in total revenue over the entire sample; $\bar{S}_{Cj}$ = an arithmetic mean value of the share of input *j* in total cost over the entire sample; $\tilde{Q}_i$ = geometric (natural logarithm) mean of output i over the entire sample; $\tilde{X}_j$ = geometric (natural logarithm) mean of input j over the entire sample. The subscripts s and *t* depict observations at the base and the current years, respectively.

According to the multilateral-translog-index formulation in Eqn. (3.8), TFP can be defined as a residual of the revenue-share weighted aggregate output quantity of the three outputs left after accounting for the cost-share weighted aggregate quantity of the four inputs that are assumed to characterize the production technology of the Canadian sawmilling industry. The exponential values of the right hand of Eqn. (3.8) provide the weighted aggregate quantities of inputs and outputs (Ghebremichael and Nanang 2004).

3.2.3 Decomposing TFP into its Main Sources

As discussed earlier, if the technology exhibits constant returns to scale, TFP is considered only as a function of technological change over time, as specified in Eqn. (3.5). That is, TFP growth can be equated to technological progress. In the absence of constant returns scale, however, TFP reflects a combination of scale and technological effects, because "it does not distinguish between pure productivity gains (i.e., shifts in the underlying isoquants or isocosts) and efficiency gains resulting from increases in the scale of operation" (Ghebremichael and Nanang 2004). In other words, the production technology is homothetic that is characterized by economies or diseconomies of scale that can be expressed as in Eqn. (3.6).

In addition to scale effects, there are many other inputs that affect productivity. They include quality of human capital (knowledge and skills of the workforce), managerial efficiency, government regulations, and relationship between labor and management. Because of these reasons, the commonly used practice is to decompose growth of the gross TFP into scale effects and pure technological change effects.

But, non-parametrically measured TFP can only be decomposed using statistical (parametric) techniques. Caves et al. (1981) suggested the model expressed in Eqn. (3.9), which appears misleadingly simple. It has been used in several studies (e.g., Freeman et al. 1987; Ghebremichael et al. 1990; Ghebremichael and Nanang 2004). It is a log-linear regression model for decomposing TFP into output and technological progress effects:

$$\ln TFP_t = \alpha + \beta \ln Q_t + \theta T_t + \varepsilon_t \tag{3.9}$$

Thus, Eqn. (3.9) states that logarithmic value of the aggregate output, Q, and a time dependent technology variable, T, can explain growth in TFP, given the error term, ε_t. Obviously, both β and θ are hypothesized to be positive in order to validate the fact that growth in TFP is a function of output growth and technological progress, respectively. In this formulation, β is interpreted as an elasticity of TFP with respect to Q_t given that all other conditions remain unchanged. θ is a marginal effect of technology on TFP, *ceteris paribus*.

In addition, the following second-degree polynomial, i.e., a quadratic function in output, is believed to be statistically effective indicator of the marginal effect of output on TFP:

$$TFP = \alpha + \beta_1 Q_t + \beta_2 Q_t^2 + \varepsilon_t \tag{3.10}$$

While β_1 is expected to be positive, showing the direct relationship between output and TFP, β_2 would indicate the *rate* (acceleration) at which TFP rises/declines as output rises/declines.

Econometricians, such as Gujarati (2003), argue that such relatively simple models are effective enough to shed light on important economic phenomena. A sample of studies that used the log-linear approach to decompose gross TFP include Freeman (1987); Ghebremichael et al. (1990); Oum and Yu (1998); and Ghebremichael and Nanang (2004).

However, an elaborated econometric model is required to decompose TFP into its major quantifiable sources. For this purpose, Denny et al. (1981) derived an econometric formulation from a long-run-dual cost function. This is described in Subsection 3.3.5, (Section 3.3), where the parametric method is explained.

3.2.4 Taxation Policy Instruments, Capital Formation, and TFP

On the importance of tax incentives and the relevant policy instruments, the Canadian House of Commons' Standing Committee on Industry (2000) concluded as follows:

> Canada's imbalanced corporate tax structure has been identified as contributing to poor investment rates and slow productivity growth in certain key industries.

It is clear that taxation comprises policy instruments that affect the way in which scarce economic resources are allocated in the public and private sectors. For example, investment incentive taxes (e.g., enhanced rate of investment tax credit, reduction of corporate income tax, and accelerated rate of capital cost allowance), are expected to stimulate investments in R&D that encourages invention, innovation, and diffusion of new technologies; and improvement in the quality of human capital. Investments in these two major strategic areas of economic growth coupled with private saving and government expenditures on infrastructure can collectively boost the processes of capital formation[15], which raises TFP. That is, in the parlance of economic growth theory, tax incentives are expected to stimulate savings, which in turn enhance capital accumulation and formation, which determine productivity growth (Kaldor 1957).

In 2004, The Canadian Chamber of Commerce (CCC), in its policy release, *2004 Policy Resolutions, Finance and Taxation*, argued strongly that Canada's effective tax rates on capital, which incorporated income tax, capital taxes, sales taxes on capital components and depreciation allowances that directly affected capital investment, were well above those in the United States and in a number of other countries, including the United Kingdom, France, Sweden, and Ireland. The CCC emphasized that Canada's high "effective tax rates on capital particularly could impede capital formation, which is critical to improving productivity and Canada's standard of living".

The Institute for Competitiveness & Prosperity, an independent think-tank, which was established in 2001 to serve as "the research arm" of Ontario's Task Force on Competitiveness, Productivity, and Economic Progress, in its 2006 annual report urged the three levels of government in Canada (federal, provincial, and municipal) to cut taxes on capital investment significantly. The Institute argued that reducing taxes on capital investment increases the rate of return on capital and encourages investment in physical capital, such as machinery, equipment, and software as well as in human capital. Its specific recommendations include elimination of federal and provincial taxes on existing

[15] Capital formation means net addition to existing real capital stock, after the removal of depreciation cost allowance.

business capital, because they are levied "even if the business is not profitable"; and consequently, the *Institute* argued, the propensity of the private business sector is dampened.

However, empirical studies (e.g, Barro 1990; King and Rebelo 1990; Jorgenson and Yun 1990; Kneller et al. 1999; Quadrini 1999) caution that the distributive role of taxation policy instruments in the demand side of the economy should not be overlooked. In fact, Kneller et al. (1999), in their detailed empirical study on "fiscal policy and growth" in the OECD, concluded that "distortionary taxation reduces growth, whilst non-distortionary taxation does not; and that productive government expenditure enhances growth, whilst non-productive expenditure does not". The authors treated income and property taxes as "distortionary" and consumption (i.e., expenditure-based) taxes as "non-distortionary". They argued that the later do not reduce the return on investment, although they might affect the labor/leisure choice. Furthermore, in evaluating the impacts of the Tax Reform Act of 1986 on U.S. economic growth, Jorgenson and Yun (1990) concluded that the most promising avenue for tax reform was to include income from household assets in the tax base, while reducing tax rates on business income.

In any case, the focus of this study is the supply side of the Canadian economy. It is understood that taxation policy instruments, such as capital cost allowance (CCA)[16], investment tax credit (ITC), and corporate income tax (CIT), influence productivity performance and thereby competitiveness of the Canadian

---

[16]CCA means the actual cost of a depreciable capital asset, accounting for depreciation, obsolescence, or depletion (Revenue Canada 2006): http://www.cra-arc.gc.ca/E/pub/tp/it285r2/it285r2-e.html, accessed Oct. 25, 2006.

sawmilling industry. Depending on the way they are implemented, taxes have either negative or positive impacts on capital formation, which is one of the determinants of TFP. That is why public policy makers and the private business sector often negotiate in search for possible optimal tax rates. For instance, "accelerated depreciation allowance", can be considered as interest-free loan to firms with the goal of increasing capital accumulation in the economy (Mankiw and Scarth 1995). It was in accordance with this macroeconomic theory's line of reasoning that the Forest Products Association of Canada (2006), in its submission to The House of Commons Standing Committee on Finance during the "2006 pre-budget consultations", argued strongly for "accelerated" CCA. Its argument was that Canada's forest products industries needed to be helped in order to maintain competitive positions in the global marketplace.

Therefore, given that this research covers a forty-year period, during which several monetary and fiscal policy changes had occurred, assessing the effects of changes in the key fiscal policy instruments on TFP is warranted. Effects of changes in three important taxation policy instruments on capital formation and on gross TFP performance of the industry are examined in this study: increases in CCA and ITC and reduction in CIT.

3.3 THE PARAMETRIC METHOD: A NEOCLASSICAL COST FUNCTION

3.3.1 Specification

The following neoclassical, long-run-total cost function is dual to the production function in Eqn. (3.1):

$$C_t = g_t\left(Q_t, W_{Kt}, W_{Lt}, W_{Et}, W_{Mt}; T_t\right) \quad (3.11)$$

where C = long-run cost; W_{it} = price of input *i* (= *K, L, E, M*); T = trend variable whose role is as described in Eqn. (3.1); and the subscript t depicts a specific year during the study period.

Eqn. (3.12) is based on the assumption that solving a general optimization problem is feasible. That is, given the exogenously determined output level, Q, and input prices W_K, W_L, W_E, *and* W_M,, firms in the sawmilling industry choose optimal combination of *K, L, E,* and *M* that would minimize total cost of production: $C = W_K K + W_L L + W_E E + W_M M$, subject to the technological constraint: $Q_t = f(K_t, L_t, E_t, M_t; T_t)$. That is, duality theory posits that, subject to given constraint conditions there exists a dual cost function corresponding to the primal production function in Eqn. (3.1).

Key Assumptions: Existence of the following four basic conditions are assumed: (i) competitive markets for both inputs and outputs where cost minimizing firms are price takers; (ii) constant returns to scale implying that equiproportional change in all inputs would lead to equiproportional change in total cost, which establishes the condition where the share of an input in total cost is equal to its price elasticity; (iii) adjustments for least-cost combination of all inputs are feasible, i.e., solution to the general optimization problem is feasible ; and (iv) technical efficiency exists in the industry.

Moreover, to meet the theoretically required conditions, the cost function in Eqn. (3.11) is expected to be characterized by positive and non-decreasing in the vectors of output level and input prices; positively and linearly homogenous as well as concave and continuous in input prices; and twice-continuously differentiable with respect to input prices.

3.3.2 Production versus Cost Function Estimation

Generally, it can be argued that either the production function in Eqn. (3.1) or the cost function in Eqn. (3.11) can be estimated to investigate the technological attributes of the Canadian sawmilling industry. However, Binswanger (1974a), Christensen and Greene (1976), and many other researchers argue that cost function estimation is more effective, because it has several advantages over production estimation that include the following:

- The serious problem of multicollinearity among input quantities that arise in estimating a production function does not exist among input prices.
- It is most likely that government policy measures regarding timber harvesting, such as the annual allowable harvest rate restrictions imposed by the provinces, would lead to situations where exogenous forces determine output levels.
- Since firms in the sawmilling industry compete with other firms in the economy for the same inputs, output levels and input prices are exogenously determined.
- Recent developments in duality theory have enhanced the appeal of the cost function estimation approach.
- Functional forms that meet theoretical requirements for estimating cost functions have been developed and verified over the years. In addition to their ability to represent very general production functions, even though they

cannot be derived from explicit production functions, such functional forms enable the researcher to compute various parameters that characterize a given production technology, such as derived demand for inputs, substitution elasticities between given pairs of inputs, own- and cross–price elasticities , and economies of scale.

3.3.3 Functional Form

Estimation of a cost function requires selection of an appropriate functional form that is sufficiently flexible to accommodate the various properties of a production technology. The literature shows there are several flexible functional forms that include the generalized Leontief (GL), the transcendental logarithmic (TL), the generalized Cobb-Douglas (GCD), and the generalized square root quadratic (GSRQ). According to Caves and Christensen (1980) it is not clear how the practitioner can choose among these forms. Among the required properties, a functional form should not impose *a priori* restrictions on input substitution possibilities and on variations in economies of scale.

Guilkey et al. (1983) concurred with the conclusions of Christensen et al. (1973) that the "TL form provides a dependable approximation to reality provided that reality is not too complex". Specifically, the TL form places no a priori restrictions on substitution possibilities among all the factors of production; and it allows scale economies to vary with level of output (Christensen and Greene 1976).

Moreover, as highlighted in Section 1.3, its extensive application indicates that the TL form has become a standard tool of researchers (e.g., Christensen and Greene 1976; Nautiyal and Singh 1983; Nautiyal and Singh 1985; Martinello 1985; Frank et al. 1990; Kant and Nautiyal 1997; Baardsen 2000). The TL used in this research takes the following form of the long-run cost function specified in Eqn. (3.11):

$$\begin{aligned}\ln C &= \alpha_0 + \gamma_Q(\ln Q) + \sum_{i=1}^{n}\beta_i(\ln W_i) + \frac{1}{2}\sum_{i}^{n}\sum_{j=1}^{n}\beta_{ij}(\ln W_i)(\ln W_j) \\ &+ \sum_{i}^{n}\gamma_{iQ}(\ln W_i)(\ln Q) + \frac{1}{2}\gamma_{QQ}(\ln Q)^2 \\ &+ \theta_T T + \frac{1}{2}\theta_{TT}T^2 + \sum_{i}^{n}\theta_{iT}(\ln W_i)(T) + \theta_{QT}(\ln Q)(T)\end{aligned} \qquad (3.12)$$

where $\beta_{ij} = \beta_{ji}$, by symmetry for i, j (= K, L, E, M); n = 4, the number of inputs; and all the terms containing T imply technological effects. Notice, the subscript, t, which depicts a specific year during the study period, is not included in Eqn. (3.12) for brevity.

In order to correspond to a well-behaved production function, a cost function must be homogeneous of degree one in input prices. That is, for a fixed level of output, total cost must increase equiproportionally for equiproportional increase in all input prices. This means that the following restrictions must be met:

$$\sum_{i}\beta_i = 1 \qquad (3.13)$$

$$\sum_{i}\gamma_{iQ} = 0 \qquad (3.14)$$

$$\sum_{i=1}^{n}\beta_{ij} = \sum_{j=1}^{n}\beta_{ji} = \sum_{i}\theta_{iT} = 0 \qquad (3.15)$$

No restrictions are imposed with respect to the substitution possibilities between pairs of inputs; the extent of economies of scale; the degree of homotheticity; and the particular form of technological change.

In accordance with microeconomic theory, it is hypothesized that for global concavity of the cost function own-price elasticities of substitution, σ_{ii}, ought to be negative at all points (Berndt and Watkins 1981). No restrictions need to be imposed on the cross-price elasticities of substitution, σ_{ij}, because they can be either positive, suggesting substitutability, or negative, suggesting complementarity.

A homothetic production structure is further restricted to be homogeneous, if and only if, the elasticity of cost with respect to output is constant. For the TL cost function, therefore, homotheticity and homogeneity restrictions are imposed as follows:

homotheticity: $\gamma_{iQ} = 0$ (3.16)

where i = K, L, E, M.

The particular restriction in Eqn. (3.16) implies that a homothetic cost function could be written as a separable function of output and input prices (Pindyck 1979).

For homogeneity, the following restrictions need to be imposed:

$$\gamma_{QQ} = \gamma_{iQ} = 0 \quad (3.17)$$

In addition, elasticities of substitution must be restricted to unity by eliminating the second-order and cross-partial terms in the input prices in Eqn. (3.12):

$$\beta_{ii} = \beta_{ij} = 0 \tag{3.18}$$

3.3.4 Derived Demand Functions for Inputs

One of the important features of the cost function estimation approach is that the derived demand functions for inputs can easily be obtained using Shephard's lemma, which uses the envelope theorem. That is,

$$\begin{aligned} \frac{\partial \ln C(.)}{\partial \ln W_i} &= \frac{\partial C}{\partial W_i}\frac{W_i}{C} = \frac{W_i X_i}{C} = S_{Ci} \\ &= \beta_i + \gamma_{iQ}(\ln Q) + \sum_{j=1}^{n} \beta_{ij}(\ln W_j) + \theta_{iT}T \end{aligned} \tag{3.19}$$

where $x_i = \dfrac{\partial C(\bullet)}{\partial W_i}$, and S_i stand for an input i quantity and a share in total cost of an input i (= K, L, E, M), respectively.

From Eqn. (3.19), a system of four cost share equations, each of which represents cost minimizing-optimal derived demand for a given input, can be formulated as follows:

$$S_{CK} = \beta_K + \gamma_{KQ}(\ln Q) + \beta_{KK}(\ln W_K) + \beta_{KL}(\ln W_L) + \beta_{KE}(\ln W_E) + \beta_{KM}(\ln W_M) + \theta_{KT}T \tag{3.20}$$

$$S_{CL} = \beta_L + \gamma_{LQ}(\ln Q) + \beta_{LL}(\ln W_L) + \beta_{LK}(\ln W_K) + \beta_{LE}(\ln W_E) + \beta_{LM}(\ln W_M) + \theta_{LT}T \tag{3.21}$$

$$S_{CE} = \beta_E + \gamma_{EQ}(\ln Q) + \beta_{EE}(\ln W_E) + \beta_{EK}(\ln W_K) + \beta_{EL}(\ln W_L) + \beta_{EM}(\ln W_M) + \theta_{ET}T \tag{3.22}$$

$$S_{CM} = \beta_M + \gamma_{MQ}(\ln Q) + \beta_{MM}(\ln W_M) + \beta_{MK}(\ln W_K) + \beta_{ML}(\ln W_L) + \beta_{ME}(\ln W_E) + \theta_{MT}T \quad (3.23$$

Hence, the optimal demand function for input i (= K, L, E, and M), is a function of all input prices, level of output, and disembodied technology. Notice that the system of four equations: (3.20) to (3.23) represents the standard *conditional factor*[17] *demand functions* for K, L, E, and M, respectively. That is, the demand for anyone of the inputs depends on the level of output, prices of all inputs that are involved in the production process, and the prevailing technology. Then, under the above-imposed restrictions, the unrestricted TL model in Eqn. (3.12) and the four restricted models, i.e., the four share equations (3.20) to (3.23), which are nested in the unrestricted TL model, form a system of five equations[18]. Furthermore, it should be noted that each of the input demand functions in equations (3.20) to (3.23) possesses important economic interpretations.

Again, application of Shephard's lemma simplifies interpretation of the input demand functions. Shephard's lemma states that the partial derivative of the long-run-dual cost function with respect to a given input's price gives the quantity of that input. That is, from Eqn. (3.11):

$$x_i = \frac{\partial g\left(Q, W_K, W_L, W_E, W_M; T\right)}{\partial W_i}, i = K, L, E, M \tag{3.24}$$

Hence, as was pointed out earlier, Eqn. (3.24) shows that the cost-minimizing optimal derived demand for the i^{th} input is a function of all factors that characterize the dual-long-run cost function: the prevailing structure (coordination) of the production technology, the level of output, the prices of all inputs, and the state of technology depicted by *T*. Then, an important question arises: What are the economic and technological effects of changes in optimal

---

[17] Following the convention of microeconomic theory, the terms **factor** and **input** are used here interchangeably to refer to any *means of production* (e.g., labor and capital).
[18] The system estimation technique is described in Subsection 3.3.7.

demand functions for inputs in response to changes in the exogenously determined output and input prices?

The sensitivity of the derived demand for input x_i to a change in the price of x_j is measured by the cross-price elasticity of demand, ε_{ij}, derived from the relevant demand equation i.e., from the share equations in (3.19) to (3.22):

$$\varepsilon_{ij} = \frac{\partial \ln x_i}{\partial \ln W_j} \tag{3.25}$$

where output quantity and prices of all other inputs, W_j, $(i \neq j)$ are fixed. Thus, a cross-price elasticity measures the percentage change in the cost minimizing demand for x_i in response to the price of input x_j, when gross output, Q, and all other input prices are held fixed. This takes effect after all input quantities are allowed to adjust to their new cost minimizing levels (Berndt and Watkins 1981). Since $\varepsilon_{ij} \neq \varepsilon_{ji}$, positive ε_{ij} implies inputs x_i and x_j are substitutes; negative ε_{ij} implies they are complements; and $\varepsilon_{ij} = 0$ reveals x_i and x_j are *independent.* The necessary condition for concavity curvature of the production function is met when all own-price elasticities, ε_{ii}, are negative[19].

[19] For more details, refer Berndt and Watkins (1981).

3.3.5 Nature and Estimates of Technological Progress

A. Perspectives on Technological Progress: an Overview

Neoclassical economic theory classifies the effects of technological progress into two categories: embodied and disembodied. Embodied technological change is realized through improved quality of inputs (e.g., knowledge and skills of the workforce). In other words, long-run *endogenous* economic growth is driven by technological progress realized through – among other things - R&D efforts of profit-maximizing economic agents (e.g., firms within the Canadian sawmilling industry). This implies that government subsidies to R&D and other incentives, such as increased investment tax credit, can stimulate long-run economic growth. However, Jones (1995) cautions that technological change that spurs long-run economic growth should be explained by parameters of both endogenous (e.g., R&D) and exogenous (e.g., population) forces. The advent of word processor computer technology is a good example of embodied technological progress (Betts 1998).

By contrast, technological change that results in an inward shift of isoquant contours of a given production function over time, with no changes in all inputs, is called disembodied technological change. In other words, more output can be produced without any change in inputs. Disembodied technological change is generally attributed to technical change, which means improvements in production techniques and/or organizational behavior that enhance productivity of existing inputs. Thus, technological progress is disembodied, if existing machinery and equipment or the whole range of productive capital stock can be made more efficient by implementing new knowledge. For example, a new version of software, once installed on an existing computer, can increase the computer's efficiency without any need for new computer and related equipment.

Learning-by-doing, which means that an industry learns better ways of doing things 11`because of knowledge accumulated through experience, is considered as *disembodied* technological progress. This is because new capital equipment is not required. Such technical progress is a result of a series of incremental improvements discovered by workers and mangers on the production line.

Thus, innovative production techniques that do not require new capital equipment characterize a disembodied technological progress. It is disembodied in that it is assumed to spread itself quickly evenly across all plant and equipment of firms operating in an industry (Betts 1998). This is particularly believed to be the case if the innovation is developed in-house, so that there are no royalties paid to an outside inventor. In effect, unpatented technical progress becomes general knowledge quickly and firms adopt the idea at little or no cost.

B. Estimating Disembodied Technological Progress

Given the justifications for incorporating a time trend variable, T, into equations (3.1) and (3.11) to capture technological change, differentiating Eqn (3.12) with respect to T yields the dual measure of TFP (Berndt and Watkins 1981). That is,

$$\frac{-\partial \ln C(.)}{\partial T} \equiv \varepsilon_{CT} = -\left[\theta_T + \theta_{TT}T + \sum_{i=1}^{n}\theta_{iT}\ln W_i + \theta_{QT}\ln Q\right] \qquad (3.26)$$

Technological progress is defined here as rate of total cost diminution, ε_{CT}, over time, *ceteris paribus.* A negative sign is attached to the partial derivative equation to ensure that a positive value of technological progress is achieved in a situation where production cost is falling (Bhattacharyya et al. 1997).

The right hand side components of Eqn. (3.26) reveal that ε_{CT} comprises the following three components (Baltagi and Griffin 1988; Bhattacharyya et al. 1997):

(i) *Pure technological change* (PTC) =

$$-\left(\theta_T + \theta_{TT} T\right) \tag{3.27}$$

(ii) *Nonneutral, factor-augmenting technological change* (NTC) =

$$-\left\{\sum_{i=1}^{n} \theta_{iT} \ln W_i\right\} \tag{3.28}$$

(iii) *Scale-augmenting technological change* (STC) =

$$-\left(\theta_{QT} \ln Q\right) \tag{3.29}$$

PTC represents effects of knowledge advancement, i.e., a disembodied technological change. Note that, since time is considered as an indicator of knowledge, PTC is measured only by the terms containing T, whose coefficients are expected to capture marginal effects of disembodied technological change [Eqn. (3.27)].

NTC is an estimate of the effects of changes in input prices as well as subsequent input substitutions on cost diminution, which are believed to be effects of embodied technological change [Eqn. (3.28)]. Observe that NTC is captured by the sum of the product of time and input price interaction parameters and the logarithmic value of the input prices.

Finally, STC represents part of the reduction in production cost attributable to increase in output realized through exploitation of scale economies [Eqn. (3.29)].

C. Hicks Neutral versus Biased Technological Change

The nature of technological change-bias has important implications. For example, the impact of new technology on employment and wages depends crucially on whether the innovation is Hicks neutral or biased. Consider, for example, a small-scale sawmill which uses capital (K) and labor (L) to produce a planned (optimal) amount of lumber, Q^*, per year. A Hicks neutral technology is one that increases productivity of both K and L proportionately. That is, the isoquant moves toward the origin along the expansion path to produce Q^* at a possible least-cost combination of K and L without changing the marginal rate of technical substitution of labor for capital. $(MRTS_{LK})$. Consequently the ratio of the price of labor to that of capital remains unchanged. That is, the ratio of wage rate to that of rental price of capital and the $MRTS_{LK}$ remain constant along the expansion path, the locus of tangencies of isoquants and isocosts.

What is the tradeoff between technological progress and employment? "Is it inevitable that Hicks neutral technological progress will lead to layoff of workers? The answer is "no"" (Betts 1998). After the sawmill has adopted the technology, it is very likely that its output will rise and it will be able to sell more of it at a competitively lower price, passing on the cost savings to consumers, who are willing to buy more of the lumber. This will be the case even if all firms in the sawmilling industry adopt the new technology. Alternatively, Betts (1998) argues that even if only one of the firms adopts the cost-saving new technology, the likelihood is greater that employment at the innovative firm will rise, because the cost reductions will cause demand for the lumber output to rise, leading to a possible increase in employment.

By contrast, a technological change is said to be "Hicks-biased", if, holding input prices constant, it changes the ratio of one input used to that of another input. For example, If the K to L ratio rose after technological progress, this would mean a "labor-saving" technological change. Thus, it is likely that this type of technological change will lead to involuntary unemployment, *ceteris paribus*. In a sense anybody who would like to work, even at a lower wage that maintains the original (optimal) ratio of labor price to that of capital cannot find a job (Betts 1998).

As specified, the TL cost function in Eqn. (3.12) does not constrain the technology to be either Hicks neutral or constant returns to scale. Thus, Hicks neutral technological change specification will require the restriction that all the interaction terms of the input prices with the time variable, T, be eliminated from Eqn. (3.12). As it stands, therefore, Eqn. (3.12) represents non-neutral technological change. That is, a biased technological change is feasible. This condition meets one of the requirements for empirical purposes.

The technology is Hicks neutral, if $\theta_{iT} = 0$ in Eqn (3.26). For no technological change, all parameters on the right hand side of Eqn (3.26) should be equal to zero. On the other hand, a rejection of Hicks-neutrality of technological change suggests biased technological change, which means that the technology is such that it saves more on some inputs than on others.

Binswanger (1974b) derives the following formula for estimating bias in utilization rate of a given input:

$$B_i = \frac{\partial S_{Ci}}{\partial T}\left(\frac{1}{S_{Ci}}\right) \qquad (3.30)$$

where B_i is the bias, T is technological change variable, as described earlier, and S_{Ci} is the share of input *i* in total cost. For the TL cost function in Eqn. (3.12), the rate of bias can be estimated easily from the following equation (Bhattacharyya et al. 1997):

$$B_i = \frac{\theta_{iT}}{S_{ci}} \qquad (3.31)$$

The meanings of the measure of bias are as follows: $B_i > 0$ implies input i-using; $B_i < 0$ implies input i-saving; and $B_i = 0$ implies Hicks neutral.

D. TFP Growth, Cost Elasticity, Returns to Scale, and Scale Economies

Given estimates of the parameters of the system of equations (3.12) and three of the four share equations (3.20) through (3.23), gross TFP growth can be decomposed into its parametric sources. Recall from the discussions in Chapter 2 that the index approach to the measurement and analysis TFP growth analysis, which is fundamentally based on Solow's (1957) pioneering work, is based on several restrictive assumptions, such as constant returns to scale; marginal cost pricing; and perfectly competitive markets for both inputs and outputs. If these assumptions are violated, the residual TFP growth is a result of the effects of several factors that include (i) non-constant returns to scale, (ii) market imperfections, (iii) economies of scale, (iv) input substitution, (v) product mix, (vi) R&D; (vii) human capital; and (viii) managerial efficiency.

Thus, in order to decompose the gross TFP into its main sources, structural information about the production technology is needed. This information can be obtained by estimating a cost function, which provides separate effects of scale economies and technical change. To accomplish this, Denny et al. (1981) derived the formulation in Eqn. (3.32) from a translog functional form of a dual-long-run cost function. This formulation provides several useful parametric measures that characterize the production technology:

$$\begin{aligned} TFP\ growth &= \left[1-\frac{\partial \ln C(.)}{\partial \ln Q}\right]\frac{d\ln Q}{dT}-\frac{\partial \ln C(.)}{\partial T} \\ &= \left[1-\left(\gamma_Q+\sum_{i=1}^{n}\gamma_{iQ}\ln W_i+\gamma_{QQ}\ln Q+\theta_{QT}T\right)\right]\dot{Q} \\ &\quad -\left(\theta_T+\theta_{TT}T+\sum_{i=1}^{n}\theta_{iT}\ln W_i+\theta_{QT}\ln Q\right) \\ &= \left(1-\varepsilon_{CQ}\right)\dot{Q}-\varepsilon_{CT} \end{aligned} \qquad (3.32)$$

where ε_{CQ} = elasticity of total cost with respect to the aggregate output;

ε_{CT} = the *dual* measure of the primal TFP growth rate due to disembodied technical progress is a measure of the rate of total cost diminution with input prices and output quantity fixed. That is, in the context of a cost function, TFP is equivalent to cost diminution, the percentage reduction in total cost resulting from technological progress and organizational improvements under given output quantity and input prices (Berndt and Watkins 1981).

Eqn. (3.32) contains two important components on which TFP growth depends: the first term which represents the scale effect is a function of ε_{CQ} and the growth rate of the aggregate output, $\dot{Q}$; and the second component, ε_{CT}, is the dual measure of the primal TFP growth, which is total cost diminution parameter (Berndt and Watkins 1981).

One important condition is implicit in Eqn. (3.32): the formulation is based on the assumption that the Canadian sawmilling industry departs from the condition of constant returns to scale and perfect competition in input and output markets. This departure relaxes the condition that restricts TFP growth to be explained only by technological change. If this assumption was violated and the production technology exhibits constant returns to scale, then ε_{CQ}= 1. Consequently, the whole scale effect disappears, leaving only ε_{CT}. This outcome makes the primal and the dual measures of TFP equivalent (Berndt 1991).

Another well-known and useful economic parameter, returns to scale (RTS), can be derived easily from ε_{CQ}. This is possible, because the TL formulation of the total cost function given in Eqn. (3.12) is a nonhomothetic, which research community uses it in analyzing industrial technologies also (e.g., Berndt and Watkins 1981; Nautiyal and Singh 1985; Freeman et al. 1987; Kant and Nautiyal 1997).

Economies of scale (ES) are other measures that characterize a production technology. Again, although they are more applicable at a firm (plant) level, the literature shows they are widely used for gaining additional characteristics of industrial production technologies (e.g., Daly and Rao 1985; Nautiyal and Singh 1985; Banskota et al. 1985; Singh and Nautiyal 1986; Baltagi and Griffin 1988; and Bhattacharyya et al. 1997).

In the context of estimating a cost function, Christensen and Greene (1976) state that it is appropriate to express ES in terms of the relationship between total cost and output along the expansion path, where input prices are constant and costs are minimized at every output level. That is, the natural way to express the extent of ES is that as the proportional increase in cost resulting from a proportional increase in the level of output, i.e., the elasticity of total cost with respect to output. Thus, ES can be expressed as one minus ε_{CQ}. That is,

$$\begin{aligned} ES &= 1 - \frac{\partial \ln C(\bullet)}{\partial \ln Q} \\ &= 1 - \left(\gamma_Q + \gamma_{QQ} + \sum_{i=1}^{n} \gamma_{iQ} \ln W_i \right) \\ &= 1 - \varepsilon_{CQ} \end{aligned} \tag{3.35}$$

where $ES > 0$ implies economies of scale; $ES < 0$ implies diseconomies of scale; and $ES = 0$ implies constant returns to scale, i.e., $\varepsilon_{CQ} = 1$.

3.3.6 Substitution and Price Elasticities of Inputs

A. Economic Implications of Substitution Elasticities

The degree of substitutability among productive factors (i.e., all means of production) has far reaching economic implications. Clearly, the whole spectrum of the literature on production economics reveals that the main purpose of the concept of production function is to describe the substitution possibilities among the inputs so that a given output level can be produced efficiently. With justifications for importance of the degree of technical substitutability of productive inputs, Sato (1977) demonstrates and provides "a more general and more meaningful class of CES production functions, i.e., non-homothetic CES functions".

Historically, Blackorby and Russell (1989) attribute the origin of input substitution elasticities to John R. Hicks (1932) who introduced it "for the purpose of analyzing changes in the income shares of labor and capital in a growing economy". Pessoa et al. (2005) elaborate that their interest in estimating elasticity of substitution between capital and labor stemmed from the fact that it determines the quantitative effect that investment distortions have on per-capita income. It is instructive to observe that these authors explore the correlation between per-capita income and TFP under a variety of substitution elasticities between capital and labor.

Arrow et al. (1961), in their classic paper, *Capital-Labor Substitution and Economic Efficiency*, demonstrate the importance of input substitution elasticities in a wide economic sphere, which includes the following five areas: the pure theory of production, the functional distribution of income, technological progress, international differences in efficiency, and the sources of comparative advantage.

The authors particularly reiterated the "fundamental economic significance of the degree of substitutability of labor and capital". It was in this classic paper that Arrow et al. (1961) discovered the celebrated Constant Elasticity of Substitution (CES) production function. Their research question was, "For what functional form would σ_{ij} be constant but not be constrained to equal unity?" They also disentangled the theory of production economics from the Cobb-Douglas unitary-constant elasticity trap and concluded, "Our empirical results imply that elasticities of substitution tend to be less than one, which contrasts strongly with the Cobb-Douglas view of the world."

In summary, a measure of the degree of input substitution has very important economic policy implications. But, it appears there is no a universally accepted measurement and analysis methodology. The following remarks show why there is fuzziness regarding which of two measures of input substitution elasticity is more credible than the other: the Allen partial elasticity of substitution (AES) or the Morishima partial elasticity of substitution (MES)?

B. Which Measure of Elasticity?

The AES, credited to Allen (1938) and the MES credited to Morishima (1967) are widely used measures. Yet, neither of them is universally accepted as a best measure. For example, Blackorby and Russell (1989), have strong objections regarding the credibility of AES. These authors, with some mathematical demonstration, argue that the AES is not a measure of the "ease" of input substitution or curvature of the isoquant; provides no information about relative factor shares, the purpose for which the elasticity of substitution was originally defined; and cannot be interpreted as a (logarithmic) derivative of a quantity ratio with respect to a price (or the marginal rate of substitution). They further make the following assertion:

> As a quantitative measure, it has no meaning; as a qualitative measure, it adds no information to that constrained in the (constant output) cross-price elasticity. In short, the AES is (incrementally) completely uninformative.

However, the literature shows extensive use of AES more than MES, establishing its credibility. Many highly regarded researchers calculate and report AES, not MES (e.g., Parks 1971; Berndt and Wood 1975; Pindyck 1979; Nautiyal and Singh 1985; Meil and Nautiyal 1988; Kant and Nautiyal 1997). Moreover, AES estimates are necessary for calculating own- and cross-price elasticities, which in turn are used for calculating the MES, as the formulas in equations (3.37) and (3.38) show.

C. Approaches to Computing AES and MES

For the TL cost function, the AES $\left(\sigma_{ij}^{A}\right)$ is calculated from the following formulae:

$$\sigma_{ij}^{A} = \frac{\beta_{ij} + S_{Ci}S_{Cj}}{S_{Ci}S_{Cj}}$$
$$i, j = K, L, E, M \quad i \neq j; \tag{3.36}$$

and the own-utilization elasticity of a factor:

$$\sigma_{ii}^{A} = \frac{\beta_{ii} + S_{Ci}^{2} - S_{Ci}}{S_{Ci}^{2}} \quad i = K, L, E, M \tag{3.37}$$

Blackorby and Russell (1989) concluded that the MES preserves the important features of the Hicksian concept in the multi-input setting; and is sufficient for assessing effects of changes in price or quantity ratios on relative input shares. An MES is calculated as the difference between the cross-price and the own-price elasticities of derived demand for a given input:

$$\sigma_{ij}^{M} = \varepsilon_{ji} - \varepsilon_{ii} \quad \text{and} \quad \sigma_{ji}^{M} = \varepsilon_{ij} - \varepsilon_{jj} \qquad (3.38)$$

where

$$\varepsilon_{ij} = S_j \sigma_{ij}^{A} \quad \text{and} \quad \varepsilon_{ii} = S_i \sigma_{ii}^{A} \qquad (3.39)$$

where ε_{ji} and ε_{ii} are the cross-price and own-price elasticities of demand for an input, respectively.

3.3.7 Estimation Techniques

It is feasible to estimate the parameters of the TL total-cost function in Eqn. (3.12) and each of the cost share equations. (3.20) to (3.23), using ordinary least squares (OLS) equation by equation. However, the OLS estimates of each equation will risk the problem of multicollinearity; and restrictions on cross-equation parameters must be imposed. In other words, since many of the coefficients in the unrestricted TL form long-run cost function and those in each of the share equations are the same, it is imperative that all these equations be estimated as a system simultaneously. This should be done not only to attain higher effectiveness of the models through minimized determinants of the cross-products' matrix, but also to obtain the estimates of $\alpha_0, \theta_T, \theta_{TT}, \gamma_Q$ and γ_{QQ}, which all appear only in the unrestricted TL form long-run cost function in Eqn. (3.12).

Because they are derived from partial differentiation of the long-run TL cost function in Eqn. (3.12, the cost share equations are not constrained by stochastic terms of their own. Moreover, following Zellner (1962), it is assumed that the disturbance terms have a joint normal distribution; and the four cost shares sum to unity at each observation, leading the disturbance terms to add up to zero at each observation. It should be expected also that the disturbance term in the unrestricted TL total cost function in Eqn. (3.12) to be correlated with the random errors of the share equations, which are nested in it.

Thus, to ensure maximum efficiency, estimating the unrestricted TL total cost function and three of the four input cost share equations as a multivariate regression system, applying the maximum likelihood estimation (MLE) method is the optimal approach. Note that MLE applied to a multi-equation system, such as a system of Eqn. (3.12) and three of the four share equations (3.20) to (3.23), chooses the set of parameters by minimizing the determinant of the residual cross-products' matrix (Berndt 1991). That is, MLE minimizes the determinant $|e'e|$.

Zellner's seemingly unrelated estimator, abbreviated as ZEF, also called in the literature as seemingly unrelated regression estimator (SURE) or the minimum chi-square estimator (Berndt 1991), is considered an efficient procedure. This is particularly the case if the iterative Zellner-efficient estimator, typically termed as IZEF is used under the assumption of *no* hetroskedasticity or autocorrelation within equations (Pindyck 1979; Berndt 1991).

Virtually all econometric computer programs, such as SAS, Stata, Limdep, SHZAM, and Microfit, which are capable of estimating parameters in systems of equations by MLE generate the value of the maximized log-likelihood function. SHAZAM©, the widely used econometrics software (White 2003)[20] is used for this research. It is capable of estimating a system of linear equations with linear restrictions imposed on the coefficients within and/or across equations. The software handles easily many types of system of linear equations, such as IZEF and I3SLS. The estimation is iterated until the parameters converge or until the maximum number of iterations specified (White 2003).

Any one of the four share equations from (3.20) to (3.23) can be dropped arbitrarily from the system to avoid singularity of the contemporaneous variance-covariance matrix. Accordingly, Eqn. (3.23) was excluded from the estimation procedure. Results obtained using this procedure are invariant to which equation is dropped from the system of the cost share equations. As Zellner (1962) notes, it is assumed that the error term in each equation is homoscedastic and non-autocorrelated. In short, this procedure has become a standard for this type of study (e. g., Christensen and Greene 1976; Meil and Nautiyal 1988; Frank et al. 1990; Kant and Nautiyal 1997; Baardsen 2000). Moreover, the procedure provides additional degrees of freedom, without adding any unrestricted regression coefficients.

Restrictions based on economic theory that are imposed on the long-run TL cost function are detailed in Subsection 3.3.3. Accordingly, six models are

[20] Copyright © 2003 by Ken J. White, the University of British Columbia, Version 9, Professional Edition, was used in this study.

tested for capability to describe the Canadian sawmilling industry's production technology. Model I is the unrestricted long-run TL cost function in Eqn. (3.12). The *test models* are Model II for Hicks-neutrality of technological change; Model III for presence of technological change; Model IV for homotheticity; Model V for homogeneity; and Model VI for unitary elasticity.

Each of the six models in the multivariate regression system was estimated simultaneously, using the IZEF procedure. Finally, the likelihood ratio test approach was used to test the various theoretical restrictions. Likelihood ratio test is a more general method that does not utilize least squares and does not rely on the normality of the error term (Pindyck and Rubinfeld 1998). However, the likelihood ratio test procedure summarized in Eqn. (3.40) was applied assuming that the error term is distributed normally. The procedure is based on the notion that, for large sample size, the test statistic, λ, follows the chi-square, χ^2, distribution.

$$\lambda = 2(ULLF - RLLF) \sim \chi_m^2 \qquad (3.40)^{21}$$

where ULLF and RLLF are the maximized values of the unrestricted and the restricted log-likelihood functions, respectively, while *m*, the subscript of χ^2, indicates the number of the imposed restrictions, which are used as degrees of freedom. Multiplying the parenthesized value in Eqn. (3.40) by two approximates the LR to chi-square distribution (Wooldridge 2006). The testing procedure

[21] This formulation is expressed in different ways in the literature. For example, $-2[L(\beta_R) - L(\beta_{UR})] \sim \chi_m^2$; (Pindyck and Rubinfeld 1998) and $-2(\ln L_0 - \ln L_1) \sim \chi_m^2$ (Berndt 1991).

involves a simple comparison of the calculated value of χ^2 with its critical value, χ_c^2, at a 5% level of significance. That is, if λ is greater than χ_c^2, then, the null should rejected.

It is understood that the traditional F-test and the likelihood ratio test should generate similar results for linear models involving large sample sizes. But, although it may be difficult to apply, depending on the type of software being used, the likelihood ratio test is more appealing because "it does not require an assumption of normality" (Pindyck and Rubinfeld 1998).

CHAPTER 4 THE DATA

Covering a forty-year period (1961-2000), the database includes multiple data sets, each of which comprising several variables. The output and input variables, including implicit derivations of some of the required variables, as well as all sources, are summarized in this chapter. Descriptions and sources of the output and input variables are detailed in Table A.1 and Table A.2 (Appendix A), respectively.

4.1 INDUSTRIAL OUTPUTS

For the purpose of this study, the sawmilling industry is Sector 251 of the 1980 Standard Industrial Classification (SIC-E-251), which includes plants primarily engaged in manufacturing lumber, both rough and dressed, and other sawmill and/or planing mill products (Statistics Canada 2005)[22]. That is, the study covers the Shingle and Shake Industry (SIC-E-2511) and the Sawmill and Planing Mill Products Industry (SIC-E-2512).

Accordingly, the industry is treated as a multi-output industry: lumber (Q_1), shakes and shingles (Q_2), and an aggregate of all the sawmilling operations' byproducts (Q_3). Byproducts include wood chips, veneer cores, slabs, edgings, sawdust, and shavings.

Lumber (SIC-E-2512): The annual series of output (Q1) were collected from Table I-4 of *Selected Forestry Statistics Canada*, The Canadian Forest Service (2006a). The quantities and values of shipments that were used to the derive implicit annual price series were collected from the Canadian Forest Service

[22] http://www.statcan.ca/english/Subjects/Standard/sic/sice80-classe.htm#251 , accessed August, 2006.

(2001), Table I-6 of *Selected Forestry Statistics Canada Special Edition – Historical Series* and from Statistics Canada Catalogue No. 35-204 and 35-250.

A series of IPPI (1992 = 100) for the Wood Industries Group (SIC-25-E) was collected from The Canadian Forest Service (2001), *Selected Forestry Statistics Canada Special Edition – Historical Series, Table V-1* for 1961-99 and from Statistics Canada Catalogue No. 62-011 for year 2000. These indices were used to convert the current dollar prices into real dollar prices.

Shakes and Shingles (SIC-E-2511): The annual series of value added in production activities were collected from Selected Forestry Statistics Canada, *Information Reports*: E-X-34 (1984), E-X-48 (1995), and Statistics Canada Catalogue No. 35-204, 35-250, and 31-203 for 1961-69. Industrial product price indices (IPPI) (1992 = 100) for these products (SIC-E-2511) were collected from The Canadian Forest Service (2001), *Selected Forestry Statistics Canada Special Edition – Historical Series, Table V-1* for 1961-99 and Statistics Canada Catalogue No. 62-011 for year 2000. The commonly used implicit quantity derivation procedure (e.g., Christensen et al. 1980; Berndt and Watkins 1981; and Christensen and Cummings 1981) was used to obtain output quantity (Q2) by dividing value added by real price.

Wood Residues: An annual series of quantities (Q3) of wood residues sold to pulp mills and their current dollar prices were collected from Manning (1972) for the period of 1961-68; and from The Canadian Forest Service (2001), *Selected Forestry Statistics Canada Special Edition – Historical Series, Table I-3* for the period of 1970-99. The quantity and price values for 1969 were determined from the average values of 1968 and 1970; and the single data point for 2000 was estimated based on the forty-year historical series. The IPPI (1992 = 100) series, which are described above, under lumber, were used to deflate the current dollar price series.

4.2 INDUSTRIAL INPUTS

A. Capital

Stock and Implicit Price by Asset Type: Statistics Canada (2001) classifies the stock of capital input in the sawmilling industry into three major asset categories: building construction (e.g., plants and offices), engineering construction (e.g., roads, dams, and bridges), and machinery and equipment.

For three data points (1998-2000), there was a problem in acquiring capital data, because of the incompatibility between the Standard Industrial Classification of 1980 (SIC-E 1980) and the North American Industrial Classification System (NAICS), which came into effect in 1998. Experts at the Investment and Capital Stock Section of Statistics Canada (2006)[23] advised that the annual expenditure totals on each of the three assets, which were reported in NAICS 3211: Sawmills and 3219: Wood Preservation, were equivalent to the expenditures in SIC-251 of 1980.

The experts advised further that the current and constant dollar values by type of asset in NAICS 321114 (SIC 2591): Wood Preservation and in NAICS 321911 (SIC 2543): Wood Window and Door Manufacturing were included in the NAICS 3211 and NAICS 3219 totals. However, the experts recommended that,

[23] Personal communications with Richard Landry, Chief, Capital Stock Section, and Mychele Gagnon, Senior Economist, Statistics Canada.

accounting for only within the range of 1% and 2% of the total capital stock value, these components were insignificant. Accordingly, the total expenditures (sum of NAICS 3211 and NAICS 3219) on the three capital assets were obtained from Statistics Canada in current and constant dollars.

Following the commonly used procedure, current dollar expenditures were then divided by the constant dollar expenditures to yield prices for each asset type. These prices were required for computing the rental price for each asset.

Rental Price of Capital: The perpetual inventory method, pioneered by Christensen and Jorgenson (1969), was used to compute rental price of capital. The data required for calculating the rental price include the following rates: corporate income tax (CIT), investment tax credit (ITC), Scotia McLeod average weighted bond yield (r), and capital cost allowance (CCA). They were obtained from the database of Ghebremichael and Nanang (2004).

The procedure for computing rental price is summarized in equations (4.1) through (4.5):

$$K_t = (1 - d_t)K_{t-1} + I_t \tag{4.1}$$

where K_t = real capital stock; K_{t-1} = real capital stock from the previous year adjusted for depreciation values; I_t = annual real-dollar investment flow; and d_t = *geometric* rate of physical depreciation of a given capital asset. The subscript t stands for an end of a specific year within the study period.

The present value of depreciation, used for the purpose of taxation, is calculated from Eqn. (4.2):

$$\mu_{it} = \frac{\delta(1+r_t)^{1/2}}{(r_t+\delta)} \tag{4.2}$$

where μ = present value of depreciation; δ = capital cost allowance (CCA); r = Scotia McLeod average weighted bond yield, representing the opportunity cost of capital (i.e., cost of financing capital); and the subscripts i and t stand for a capital asset and a year, respectively. A tax multiplier is calculated as follows:

$$\mathrm{m}_{\mathrm{it}} = \frac{1 - \mathrm{k}_{\mathrm{it}} - \mathrm{u}_{\mathrm{t}}\, \mu_{it}}{1 - \mathrm{u}_{\mathrm{t}}} \tag{4.3}$$

where m is tax multiplier, while κ_{it}, and u_t, stand for ITC and CIT, respectively.

Furthermore, the capital gains rate must be calculated. It was estimated using a 5-year moving average of the natural logarithm of an asset's price. That is,

$$\eta_{it} = \frac{\ln\left(\frac{PA_{it}}{PA_{it-5}}\right)}{5} \tag{4.4}$$

Finally, following Christensen and Jorgenson (1969), the rental price of an asset was generated from the following formula:

$$\rho_{it} = m_{it}(r_t PA_{it-1} + d_i PA_{it} - \eta_t PA_{it}) + \tau_t PA_{it} \tag{4.5}$$

where ρ = the rental price; PA = price of a given capital asset i (= machinery and equipment, engineering, and building); d = rate of physical depreciation of an asset, computed using the double declining method; η = capital gains rate from Eqn. (4.4); τ = property tax rate used only for building components.

This approach to computing rental price of a capital asset has important economic implications. The rental price calculated with the formula in Eqn. (4.5) captures the true opportunity cost i.e., user cost, of a capital asset. This is because the equation takes into account effects of capital cost allowance, corporate income tax, investment tax credit, property tax, interest cost of the funds tied up in the physical asset, economic depreciation, and capital gains and losses due to changes in an asset price.

B. Labor: Two sets of labor input in production and in management activities were identified. The values for each set were collected from the The Canadian Forest Service (2006a), Table III-11A in *Selected Forestry Statistics Canada* (details in Table A.2). The annual number of workers in production (LP = labor in production) was subtracted from the total number of employees in both production and management to determine the total number of employees in management and administration (LM = labor in management). Similarly, wages in production (WP) were subtracted from *total salaries and wages* reported for both production and management to obtain total wages in management (WM). Then, WP divided by LP provided labor price in production (W_1), while WM divided by LM provided labor price in management and administration (W_2). Finally, a weighted average price of labor, W_L,, was calculated as follows:

$$W_L = \frac{W_1 LP + W_2 LM}{LP + LM} \qquad (4.6)$$

In Eqn. (4.6), LP + LM = QL, total quantity of labor input.

C. Energy: The quantity of energy was derived implicitly. Total cost of fuels and electricity were collected from the Canadian Forest Service (2006), Table III-11A in *Selected Forestry Statistics Canada* (details in Table A.2). Then, industrial energy consumption price indices were collected from *Economic Reference Tables* (old title) and *Fiscal Reference Tables* (current title) of the Department of Finance Canada (2006) for deriving implicit energy quantity.

D. Raw material: A complete annual quantities of harvested sawlogs, the sole raw material inputs, were collected from the Canadian Forest Service (2006a), Selected Forestry Statistics Canada, Table I-1 (details in Table A.2). Implicit prices were derived from quantity and value of shipments collected from various issues of Statistics Canada Catalogue Number 25-201.

All previous studies used the term "roundwood" or simply "wood" as one of the four inputs that described the production function of the sawmilling/lumber industry (e.g., Martinello 1985; Nautiyal and Singh 1985; Singh and Nautiyal 1986; Meil and Nautiyal 1988; and Meil et al. 1988; Puttock and Prescott 1992). Although not clearly stated, it is believed that the term "roundwood" in these studies is supposed to mean *sawlogs*; because, based on *end-use*, Statistics Canada classifies harvested timber into four categories of roundwood: sawlogs (logs & bolts), pulpwood, other industrial roundwood (e.g., railway ties and poles), and fuelwood and firewood (The Canadian Forest Service (2006)[24].

[24] http://www2.nrcan.gc.ca/cfs-scf/selfor/default.html, accessed October 05, 2006.

CHAPTER 5 NONPARAMETRIC METHOD RESULTS

The previous four chapters have established the necessary groundwork for the empirical work. In this chapter, the nonparametric empirical findings generated with the multilateral index model are discussed. The parametric results are discussed in Chapter 6. First, historical trends in the data are analyzed in Section 5.1 to make preliminary observations that are helpful in interpreting the nonparametric empirical results.

5.1 HISTORICAL TRENDS IN THE DATA

The first step involved analysis of input and output quantity indices as well as input shares in total cost and output shares in total revenue. This preliminary analysis is crucial, because it reveals anomalies in the data, allowing the researcher to take remedial measures; enhances credibility and scope of the empirical findings; and provides useful insights into the dynamics of technological attributes, such as partial and total factor productivity measures (Frank et al. 1990, Ghebremichael et al. 1990, Ghebremichael and Nanang 2004).

In this section, the historical trends in factor shares in total cost, the Tornqvist quantity indices of inputs, and output shares in total revenue, are discussed. While average annual results and graphs are used for the discussions here, the complete time series of the results of cost shares, input quantity indices, and revenue shares, respectively, are reported in Tables B.1, B.2, and B.3 (Appendix B).

5.1.1 Factor Shares in Total Cost

Total cost refers to the long-run cost of production, which includes annual expenditures on the factors of production, which are capital, labor, energy, and sawlogs (raw material). A factor's share in total cost is the ratio of the annual expenditure on that input to the annual total cost of production.

Input-cost shares provide useful information on resource allocation by revealing the inputs that account for the greatest proportion of the total cost of production. Cost shares signal inputs that should be targeted for cost minimization and productivity improvements. As expected, the raw material accounted for the largest average annual share of 69% over the study period (Table 5.1). Energy accounted for the least average annual share (roughly 1.5% to 3.0%), followed by capital, which accounted for an average annual share ranging from 8% to 10%; and labor's share declined from more than 46% in the 1960s to roughly 21% in the 1990s (Table 5.1 and Fig. 5.1).

Table 5.1. Average annual input cost shares at ten-year intervals for the Canadian sawmilling industry

	Shares (%)			
Period	Capital	Labor	Energy	Material
1961-70	8.64	46.26	1.51	43.59
1971-80	7.55	40.35	1.83	50.27
1981-90	9.72	31.82	2.86	55.60
1991-00	8.43	20.74	2.21	68.62

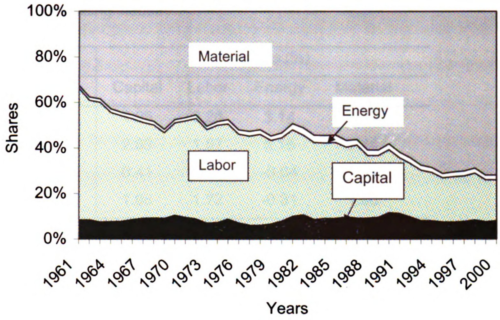

Figure 5.1. Input cost shares in total cost, the Canadian sawmilling industry: 1961-00.

When analyzing an industrial cost structure, it is important to bear in mind that changes in cost shares embody movements in both the price and the quantity of all inputs. Even if there is no change in the price of a given input (e.g., labor), a change in its cost share can also be influenced by changes in the prices of other inputs (Freeman et al. 1987). Thus, it is imperative to think of changes in cost shares as being made up of two components: one that depends on the given input's own price and quantity and the other on the prices and quantities of all other inputs.

5.1.2 Input Quantities

Table 5.2 summarizes ten-year average annual changes in quantities of the inputs, while Figure 5.2 presents their trends over the forty-year period.

Table 5.2. Average annual changes in input quantities at ten-year intervals for the Canadian sawmilling industry

	Changes (%)			
Period	Capital	Labor	Energy	Material
1961-70	1.95	0.26	3.14	2.47
1971-80	2.63	1.57	5.15	2.14
1981-90	0.41	-0.80	-0.04	1.31
1991-00	1.08	1.72	-0.31	1.86

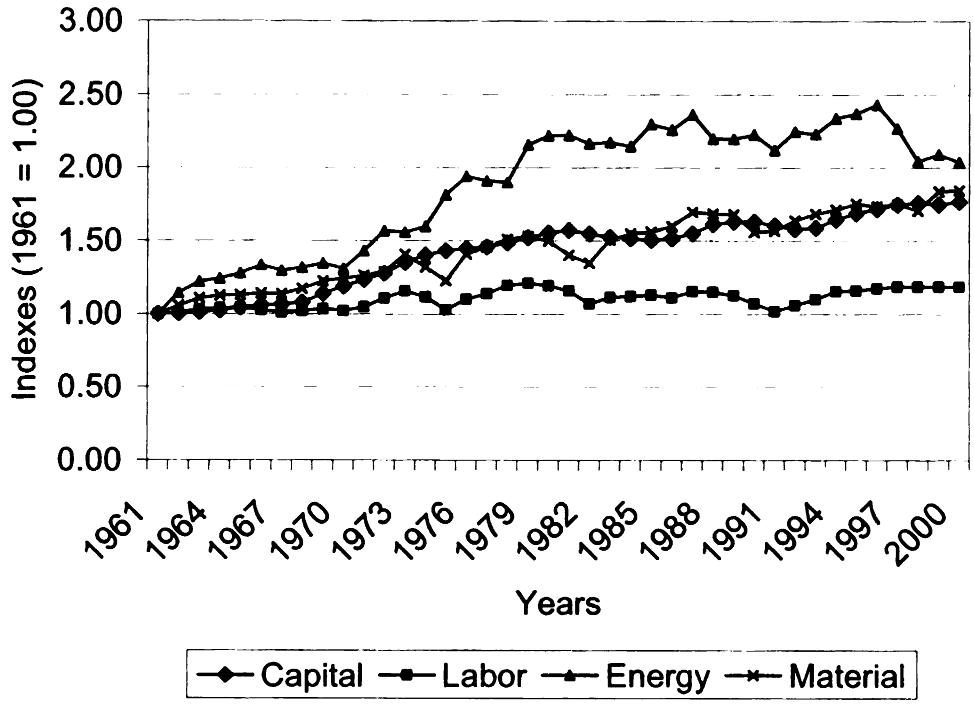

Figure 5.2. Trends in input quantities for the Canadian sawmilling industry: 1961-00.

Generally, input quantities trended upwards over the study period (Fig. 5.2). During the decades of the 1960s and 1970s, capital input increased at an average annual rate of 2%. In the 1980s, however, its growth rate was low, just 0.4%. This is despite the appearance of some improvements in investments in the 1990s. In the two decades of the 1960s and 1970s, labor input averaged 0.3% and 1.6%, respectively, while energy input increased at the rates of 3.0% and 5% (Table 5.2 and Fig. 5.2). The raw material input (the sawlogs) maintained an average annual growth rate of 2% during the first two decades of the 1960s and the 1970s. But, the average annual growth rate of sawlogs' utilization during the 1980s and 1990s was less than 2%. This indicates that there were slowdowns in production operations during the two decades.

5.1.3 Output Shares in Total Revenue

As detailed in Section 4.1, the Canadian sawmilling industry is a multi-output industry. For the purpose of this study, the sawmilling industry is a multioutput industry, producing three main components: lumber, shakes and shingles, and wood residues. An output's share in total revenue indicates the scale of its commercial importance.

Table 5.3. Average annual output revenue shares at ten-year intervals for the Canadian sawmilling industry

	Shares (%)		
Period	Lumber	Shakes & Shingles	Wood Residues
1961-70	85.13	1.34	13.53
1971-80	87.14	1.42	11.45
1981-90	81.09	1.01	17.90
1991-00	80.73	0.71	18.56

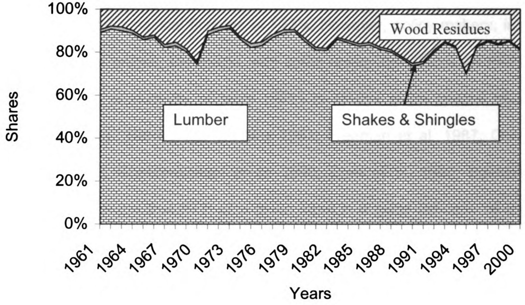

Figure 5.3. Output shares in percent of total revenue for the Canadian sawmilling industry: 1961-00.

Accounting for more than 80% share in total revenue, lumber was the industry's most important product (Table 5.3 and Fig. 5.3). Wood residues, the byproducts of sawmilling operations, accounted for the second largest annual revenue shares, ranging from 14% to 19%. By contrast, shakes and shingles appear to have been losing their relative economic significance over the years. They accounted for just 1% of the total revenue in the 1960s and 0.7% in the 1990s (Table 5.3).

5.2 PARTIAL FACTOR PRODUCTIVITIES

In this section, the levels of partial factor productivities (PFPs) and their average annual growth rates are examined. Graphs and ten-year-period average annual changes are used for the discussion, while Table C.1 (Appendix C) presents the complete time series of the PFP indices.

For the reasons detailed in B of Subsection 3.2.1, many researchers are reluctant to report empirical findings of PFPs. However, policy makers, industry executives, labor unions, the media, and some researchers focus on PFPs. For example, partial productivity of labor (PPL) is always given special attention. Researchers (e.g., Berndt and Watkins 1981; Freeman et al. 1987; Oum and Tretheway 1989; Ghebremichael et al. 1990; Oum et al. 1990; Baldwin and Dhaliwal 2000) argue that PFP of a given input is a good indicator of a given input's contribution to the growth of an industrial aggregate output.

Based on this concept, the major public agencies in North America, the U.S. Bureau of Labor Statistics and Statistics Canada, calculate and record annual series of PPL. They call it simply "labor productivity". However, focusing on PPL misleadingly implies that other inputs, such as capital, energy, material, and technological progress make less important contributions to output growth.

Levels and growth rates of the PFP of each of the four inputs are used here to provide additional insights into the production structure and productivity performance of the Canadian sawmilling industry over the years, 1961-2000.

Table 5.4. Average annual changes in PFPs at ten-year intervals for the Canadian sawmilling industry

Period	Changes (%)			
	PPK	PPL	PPE	PPM
1961-70	3.37	5.04	2.24	2.78
1971-80	3.20	3.87	1.07	3.23
1981-90	3.86	4.87	4.09	2.67
1991-00	3.17	2.49	4.72	2.31

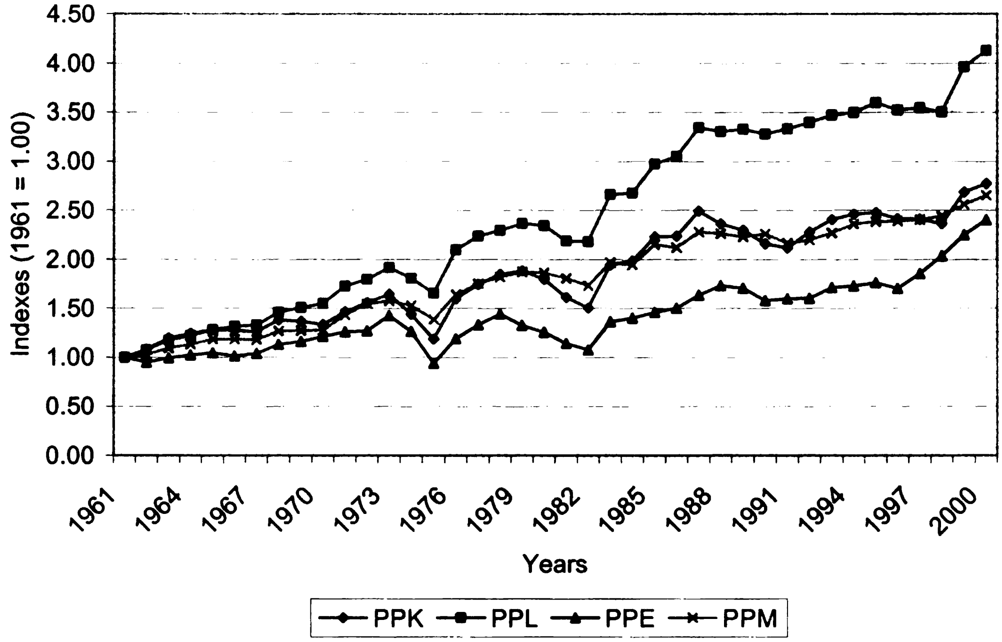

Figure 5. 4. Trends in PFPs for the Canadian sawmilling industry: 1961-00.

As described earlier, PPK, PPL, PPE, and PPM stand for partial productivities of capital, labor, energy, and Material, respectively. Differing in growth rates, all PFPs took upward trends over the study period (Table 5.4 and Fig. 5.4). These trends indicate that either use of each input declined steadily over the study period or the industry had experienced technical and/or technological improvements. This is the crux of the difficulty associated with interpreting PFPs.

The average annual growth rate of PPK remained within the range of 3% and 4% over the four periods, while that of PPL was within the range of 5% in the 1960s and 2% in the 1990s (Table 5.4). The growth rate of PPE ranged from a low of 1% in the 1970s to roughly 5% in the 1990s, while PPM maintained an approximate rate of 3% during each of the three decade-periods of the 1960s, the 1970s, and the 1980s and just over 2% during the 1990s (Table 5.4 and Fig. 5.4).

PFPs can easily be related to their respective quantities that are utilized in the production process. Obviously, the higher the quantity of a given input used, the lower the PFP of that input. Consider, for example, trends in PPE. The rapid growth in its consumed quantity (Fig. 5.2) has resulted in its lowest partial productivity (Fig. 5.4). By contrast, the Canadian sawmilling industry attained a high PPL (Table 5.4 Fig. 5.4) since labor input has been relatively low and steadily declining (Fig. 5.2).

5.3 TOTAL FACTOR PRODUCTIVITY

5.3.1 Background

What were the levels and growth rates of the gross TFP in the Canadian sawmilling industry over the forty-year study period? And, what were the main sources of TFP? These are the two interrelated research questions posed under Theme 1 in Section 1.4. The discussion in this section addresses these questions. First, as a brief reminder of the details given in Chapter 2, highlighting the complexities that underlie measurement and analysis of TFP is in order.

Growth in TFP is the difference between aggregate output growth weighted by revenue shares and aggregate input growth weighted by cost shares. If the technology exhibits constant returns to scale, TFP is considered only as a function of technological change. Thus, its growth is interpreted here as a measure of "supernormal" gains associated with investments in R&D that lead to technical and technological improvements (Lipsey and Carlaw 2004). In the absence of constant returns scale, however, the gross TFP index reflects a combination of scale and technological effects, because it does not distinguish between pure productivity gains (i.e., shifts in the underlying isoquants or isocosts) and efficiency gains resulting from increases in the scale of operation.

There are many quantitative and qualitative productive inputs each of which is capable of influencing TFP growth. They include managerial efficiency, government regulations, labor and management relations, human capital (knowledge and skills), R&D expenditures, and taxation policy instruments. Thus, TFP growth has to be decomposed into scale effects and pure technological change effects. This aspect of the analysis is detailed in Chapter 6, where the parametric results are discussed.

Moreover, the model formulated in Eqn. (3.8) shows that TFP is a residual that cannot be attributed to an aggregate of given quantity of inputs. In effect, the TFP results discussed here cannot be attributed to the four inputs of capital, labor, energy, and material that are assumed to characterize the Canadian sawmilling industry's production technology. With these caveats in mind, the nonparametric, index form TFP results are discussed next.

5.3.2 Nonparametric Measures of Gross Total Factor Productivity

The complete forty-year series of TFP results that were generated using the multilateral index model formulated in Eqn. (3.7) and aggregate output and input quantities are reported in Table C.2 (Appendix C). A summary of average annual changes in aggregate output and input quantities and that of the gross TFP along with a graph that depicts annual series of these three variables are used for the discussion here.

Aggregate output has been rising at a faster rate than that of aggregate input, leading to a modest growth rate of TFP (Table 5.5 and Fig. 5.5).

Table 5.5 Average annual changes in aggregate output, input, and gross TFP at ten- and forty-year intervals for the Canadian sawmilling industry: 1961-2000

Period	Average annual changes (%)		
	Output	Input	TFP
1961-70	5.33	2.69	2.45
1971-80	5.85	4.23	1.26
1981-90	4.23	1.11	2.98
1991-00	4.24	3.58	0.62
1961-00	4.56	2.52	1.89

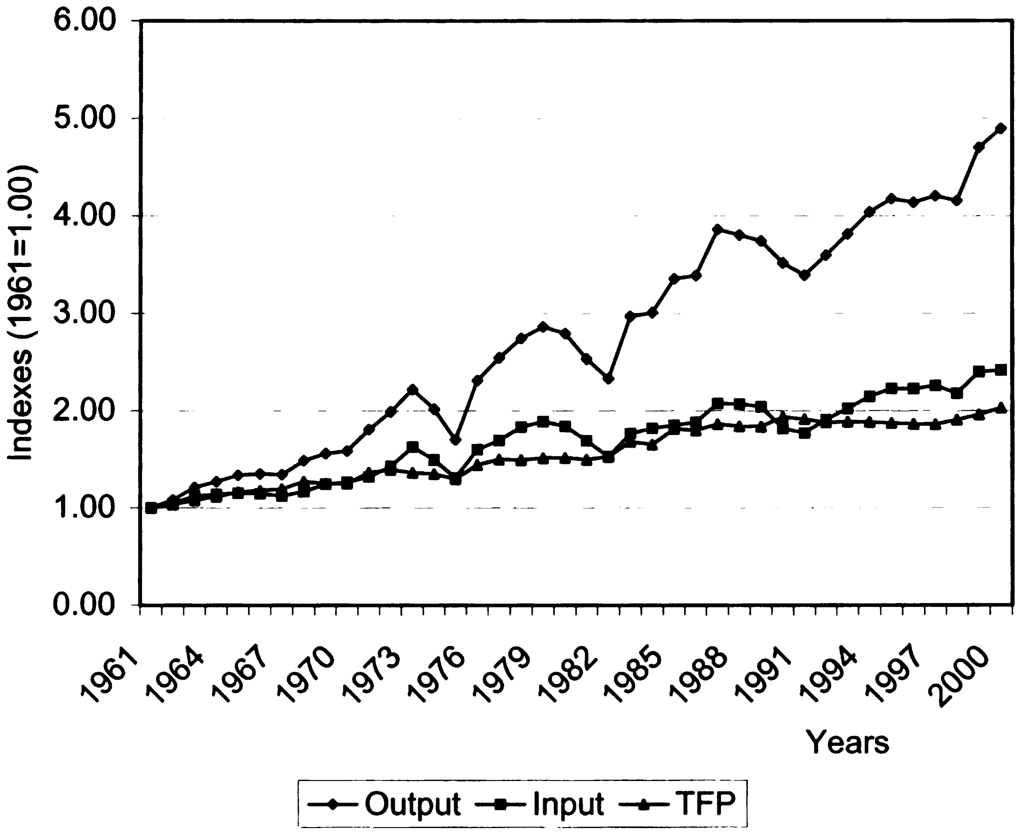

Figure 5. 5. Trends in output, input, and TFP for the Canadian sawmilling industry:
1961-00.

Examination of the growth rates by decade indicates different efficiency scenarios in production processes. During the decade of the 1960s (1961-70), more than 5% average annual growth in aggregate output and approximately 3% in aggregate input growth resulted in roughly 2.5% growth in TFP (Table 5.5). During the decade of the 1970s (1971-80), although aggregate output rose at an average annual rate of 6%, a relatively faster growth rate than previous years, aggregate input quantity also grew at a relatively faster rate of more than 4%. Consequently, the industry's TFP growth rate was at 1.3%, which is considerably lower than previous years. Furthermore, the Canadian sawmilling industry experienced considerably sluggish TFP growth of 0.62% in the 1990s (Table 5.5). The forty-year average annual growth rates also show similar trends: roughly 5% and 3% for aggregate output and aggregate input, respectively, resulting in approximately 2% average annual growth in TFP (Table 5.5).

What are the causes of the industry's TFP fluctuation and sluggishness? It is understood that TFP performance of the Canadian sawmilling industry is linked to the North American economic climate – particularly to that of the United States. Nearly 90% of Canada's lumber is exported to the U.S. market. If there were productivity slowdowns in the American economy, then stagnation in housing starts sets in, leading to substantial decline in demand for Canadian lumber. Extensive literature shows that this is the scenario that prevailed in the early 1970s and in the 1980s up to the mid-1990s (e.g., Wolf 1996 and Hulten 2001).

Covering the 1970s and the 1990s, researchers at the Brookings Institute (e.g., Griliches 1989; Bosworth and Perry 1994; Nordhaus 2002) studied productivity performance of the American economy. They attributed "productivity stagnation in the early 1970s" to a number of market and non-market forces that include (i) rising energy prices; (ii) a high inflation rate; (iii) declining investments in R&D; (iv) "deteriorating" quality of human capital; (v) "depleted possibilities for invention"; and (vi) "societal laziness".

Thus, economic conditions in the U.S. coupled with performance of the Canadian economy should have had significant effects on the Canadian sawmilling industry's TFP performance.

5.3.3 Effects of Selected Determinants on TFP Growth

The results discussed above deal with the trends in gross TFP indices. Here, parametric and nonparametric approaches are used to assess effects of variables that are commonly deemed as major determinants of TFP. The parametric results from the stochastic regression models are discussed first. Then, to shed some light on the research question under Theme 2, effects of tax incentives on TFP growth and capital formation are analyzed.

A. Decomposing TFP into its Main Sources

Effects of output growth and time dependent technology are commonly accepted main sources of TFP growth. To minimize autocorrelation effects, the GLS method, with the commonly used Cochrane-Orcutt iterative estimation procedure, was used to generate the results reported in Table 5.6. The GLS method "rids an equation of pure first-order serial correlation and in the process restores the minimum variance to its estimation" (Studenmund 2006)[25].

The two regression models, which are formulated and detailed in equations (3.9) and (3.10) (Subsection 3.2.3), are rewritten below for ease of reference; and results of each model are reported in Table 5.6.

Model 1:

$$TFP = \alpha + \beta_1 Q_t + \beta_2 Q_t^2 + \varepsilon_t$$

Model 2:

$$\ln TFP_t = \alpha + \beta \ln Q_t + \theta T_t + \varepsilon_t$$

[25] In **SHAZAM**, the **AUTO** command performs this procedure.

Table 5.6. GLS regressions of TFP with the Cochrane-Orcutt iterative estimation procedure for the Canadian sawmilling industry

Variable	Model 1	Model 2
	Parameter (t-ratio)	Parameter (t-ratio)
Constant	0.6510 (6.7290)***	0.0261(1.0770)
Q	0.4429 (6.0670)***	-------------
Q^2	-0.0353(-2.847)***	-------------
LnQ	-----------------	0.2887(6.2680)***
T	--------------------	0.0062(3.055)***
Test statistics:		
R^2	0.9811	0.9870
DW	1.6320	1.7945

Note: *** Indicates significance at the 1% level.

The two regression models performed fairly well. The estimated coefficients are highly significant; and their signs meet the hypotheses that were set forth in accordance with economic theory; the R^2 of each model is more than 98%; and the Durbin-Watson (DW) is 1.632 for Model 1 and 1.795 for Model 2 (Table 5.6). Hence, as expected, TFP growth is highly dependent on output growth and technological progress.

Results of the regression for Model 1 show that the marginal effect of increase in aggregate output on TFP growth is 0.4429, *ceteris paribus*. But, the coefficient on Q^2 reveals that TFP rose (accelerated) with output at a declining rate of 3.5%.

According to Model 2, the log-linear model in the aggregate output, elasticity of TFP with respect to Q, is roughly 0.3. This means that a 1% increase in Q would generate approximately 0.3% average annual growth in TFP, *ceteris paribus*. The coefficient on T, on the other hand, indicates the expected marginal effect of technological progress on TFP growth. It shows the average annual TFP growth rate was 0.62% over the study period, *ceteris paribus*.

B. Taxation, Capital Formation, and TFP: a Simulation Analysis

The research question under Theme 2 poses the following question: What were the effects of annual increases in the rates of capital cost allowance and income tax credit and annual reductions in the rate of corporate income tax on capital formation and on TFP growth? The following discussions on the simulation procedure and empirical results are intended to address this research question.

B.1. Assumptions and Procedure

Assumptions

This analysis is based on the assumption that all three simulated fiscal policy actions would lead to enhanced rate of capital formation and improved TFP performance. These potential improvements were expected to be reflected through a higher share of capital in total cost; a higher capital intensity in the production technology; and a slightly lower gross TFP due to the fact that aggregate output and the other three inputs (labor, energy, and Material) are fixed. This is because capital formation increases the available capital stock, which in turn raises the aggregate input quantity. Consequently, the post-policy TFP (TFP2) should be expected to be slightly lower than the pre-policy TFP (TFP1).

Procedure

A brief on the empirical procedure is provided here. In order to get measurable differences between the *without* and the *with* policy actions, the following relatively significant changes were made on each taxation instrument arbitrarily:

CCA: For building and engineering assets, the CCA rate was doubled from 4% to 8% for the 1961 to 1987 period; and from 5% to 10% for the 1988 to 2000 period. For machinery and equipment assets, it was doubled to 40% from a constant rate of 20% over the study period (1961to 2000).

ITC: Assuming a 5% benchmark, the ITC rate was raised from 0% to 5% for the 1961 to 1974 period; doubled from 5% to 10% for the 1975 to 1978 period; from 7% to 14% for the 1979 to 1986 period; and from 5% to 10% for the year of 1987; raised from 0% to 5% for the 1989 to 1995 period; and doubled from 5% to 10% for the 1997 to 2000 period.

CIT: A reduction of 50% of the original rate that varied between 43.40% and 53.41% over the study period was made.

Asset Prices: Following the pre-taxation change techniques, which are summarized from Eqn. (4.1) through Eqn. (4.5), annual rental prices of each of the three capital assets were re-calculated. Then, quantity weighted capital service price and a total cost of capital were re-computed. Finally, the multilateral index model in Eqn. (3.7) was re-run to compute TFP2.

B.2. Results with Changes in Taxation

The share of capital in total cost and capital intensity are discussed first. These measures are good indicators of capital formation.

Cost Shares

These shares are implicit measures of capital formation as a result of the simulated tax incentives, which are expected to stimulate investment. The complete annual series of the cost shares of all inputs *with* the changes is reported in Table D.1 (Appendix D), while those shares of capital for *without* and *with* the changes along with percentage differences are reported in Table D.2 (Appendix D).

Higher average annual shares of capital in total cost associated *with* the changes in the taxation policy instruments than those *without* indicate that the tax incentives enhanced capital formation (Fig. 5.6 and Table 5.7). The average annual shares of capital in total cost *without* the changes ranged between 8% and 10%, roughly, whilst those *with* the changes ranged between 12% and 14% (Table 5.7).

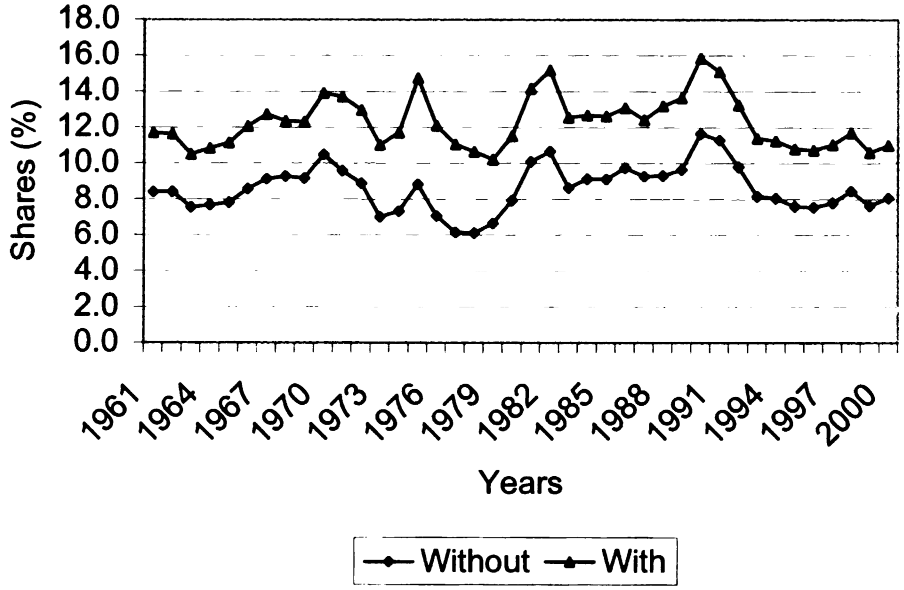

Figure 5. 6. Shares of capital in total cost *without* and *with* the changes in taxation for the Canadian sawmilling industry: 1961-00.

Table 5.7. Average annual shares of capital in total cost *without* and *with* the changes in taxation at ten- and forty-year intervals for the Canadian sawmilling industry

Period	Changes (%)	
	Without	With
1961-70	8.6	11.9
1971-80	7.5	12.0
1981-90	9.7	13.5
1991-00	8.4	11.7
1961-00	8.6	12.3

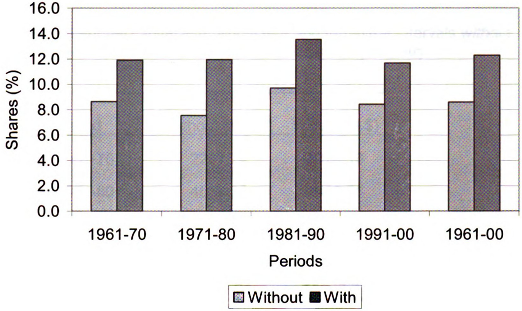

Figure 5. 7. Average annual shares of capital in total cost *without* and *with* the changes in taxation at ten- and forty-year intervals for the Canadian sawmilling industry

The forty-year average annual (1961-00) also depicts similar outcomes. The highest capital formation occurred during the period of 1981-90 (Fig. 5.7).

Capital Intensity

Capital intensity is a term commonly used in economics to describe real capital stock per worker in a production process (Pearce 1992, Mankiw and Scarth 1995). High capital intensity indicates a production technology characterized by more machinery, equipment, etc; and presumably, higher productivity.

Complete annual series of capital intensity results, without and with changes in the taxation policy instruments, are reported in Table D.3 (Appendix D).

Table 5.8. Average annual capital intensity at ten- and forty-year intervals *without* and *with* the changes in taxation for the Canadian sawmilling industry

Period	Without (real $)	With (real $)
1961-70	2297.24	3275.10
1971-80	4557.23	7625.31
1981-90	13538.17	19643.58
1991-00	21219.02	30510.82
1961-00	10402.91	15263.70

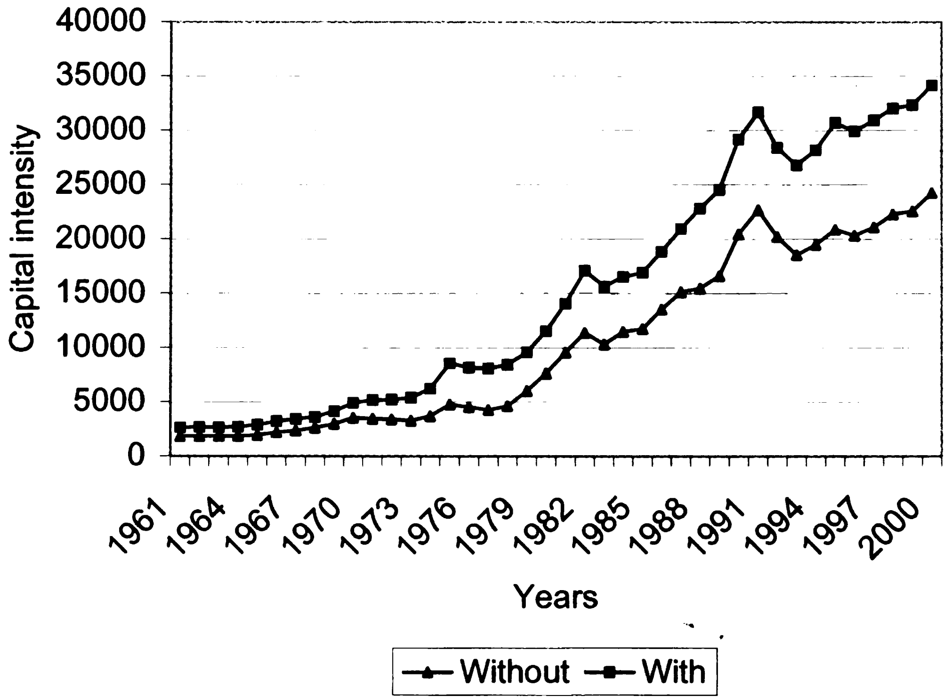

Figure 5. 8. Capital intensity *without* and *with* the changes in taxation for the Canadian sawmilling industry: 1961-00.

Capital intensity with the changes in the three taxation policy instruments shows steady growth significantly above that without the changes (Table 5.8 and Fig. 5.8).

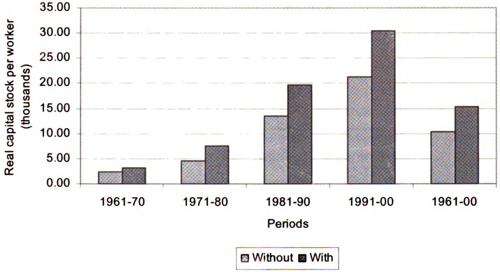

Figure 5. 9. Average annual capital intensity at ten- and forty-year intervals *without* and *with* the changes in taxation for the Canadian sawmilling industry.

The intensity *with* changes followed rapidly rising trends (Fig. 5.8). The average annual intensity of the 1960s (1961-70) was real $2,297.24 per worker for the *without* and real $3,275.10 per worker for *with* the changes (Table 5.8). By contrast, in the 1990s (1991-00), it was real $21,219.02 per worker for the *without* and real $30,510.82 per worker for *with* the changes. Over the forty-year study period (1961-00), average annual intensities were real $10,402.91 per worker for the *without* and real $15,263.70 per worker for *with* the changes (Table 5.8).

The highest intensity *with* the changes occurred during the period of 1991-00 (Fig. 5.9). It appears that the economic climate during that period was conducive for the industry to invest in various types of capital assets.

Total Factor Productivity (TFP)

For comparative purposes, a complete annual series of both TFP1 and TFP2 are reported in Table D.4 (Appendix D).

Table 5.9. Average annual values of TFP1 and TFP2 and their difference

Period	TFP1 (without)	TFP2 (with)	Marginal difference (%) = (TFP2-TFP1)x100
1961-70	1.1541	1.1512	-0.2877
1971-80	1.4239	1.4011	-2.2861
1981-90	1.7446	1.7099	-3.4721
1991-00	1.9054	1.8642	-4.1243
1961-00	1.5570	1.5316	-2.5425

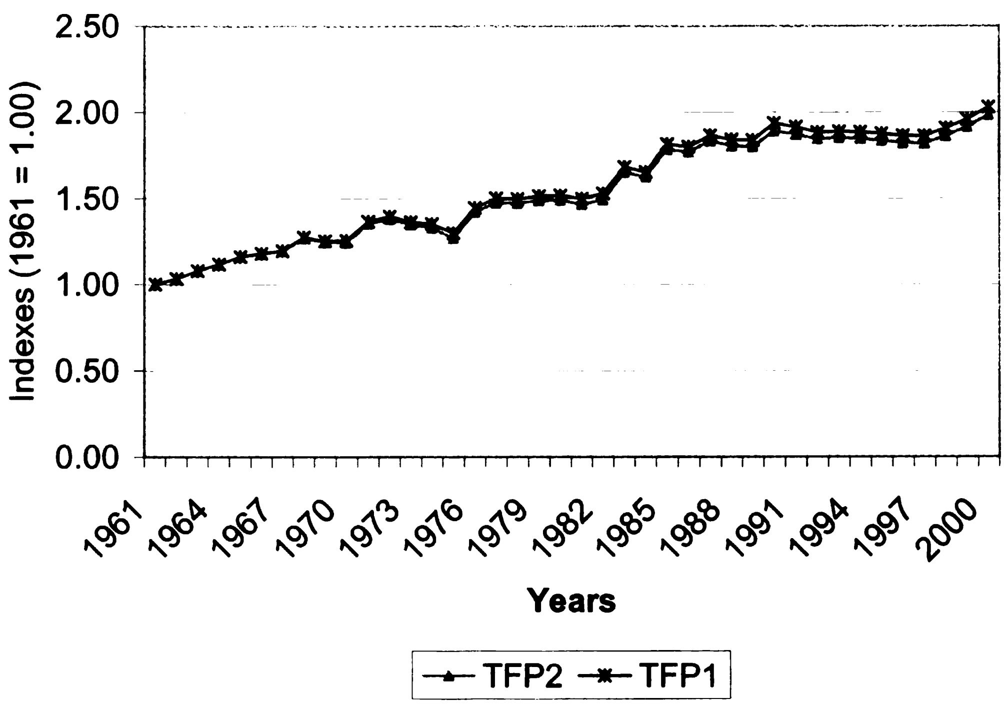

Figure 5. 10. TFP1 and TFP2 for the Canadian sawmilling industry: 1961-00.

As expected, TFP2 is slightly lower than TFP1 (Fig. 5.10). This is a result of higher capital formation, motivated by the tax incentives. Consequently, the aggregate quantity of the inputs increased significantly, while the *aggregate* output and the other inputs (labor, energy, and material) were unchanged. The highest average annual difference between TFP2 and TFP1 (over 4%) occurred during the 1990s (1991-00), the period during which capital intensity was the highest (Table 5.9 and Fig.5.9).

As detailed in Section 3.2, TFP growth is the revenue-share weighted aggregate output growth minus the cost-share weighted aggregate input growth. Under these conditions, therefore, the multilateral index model, which is summarized in Eqn. (3.8), has generated the expected results: a larger share of capital in total cost, a higher intensity of capital, and a relatively lower TFP; which are all results of the tax incentives.

In closing, a caveat on the above findings is in order. To examine impacts of changes in various taxation policy instruments on the supply and the demand sides of the Canadian economy, inter- and intra-industry transaction models, such as the commonly used computable general equilibrium (CGE) model, need to be developed.

Therefore, it can be concluded that robustness of the multilateral index techniques and the reliability of the findings have been achieved. The arguments of think tank organizations, such as the Forest Products Association of Canada (2006) and the Institute for Competitiveness & Prosperity (2006) for increases in CCA and ITC and for reduction of CIT are justifiable.

CHAPTER 6 PARAMETRIC METHOD RESULTS

The parametric method, estimation of a long-run dual neoclassical cost function, is described in Section 3.3. The empirical models' specification, the translog functional formulation, the estimation techniques, and the various parametric measures that can characterize the Canadian sawmilling industry's production technology are detailed in that section.

In this chapter, results of this parametric empirical method are reported and discussed. The procedure for selecting the best model out of the six empirical models, factor substitution and price elasticities, and decomposition of TFP growth into its parametric sources along with other technological attributes are summarized and discussed in sections 6.1, 6.2, and 6.3, respectively. Finally, results of this study are compared with those of previous studies in Section 6.4.

6.1 RESULTS AND MODEL SELECTION PROCEDURE

As detailed in Subsection 3.3.7, Model I, which is the unrestricted TL form of the long-run total cost function, and the first three of the four cost-share equations: (31.20) to (3.22), formed a system of four equations. Eqn. (3.23) was dropped out of the system arbitrarily. The systems approach is used to deal with cross equation restrictions and the variance-covariance matrix.

The optimal procedure is to simultaneously estimate the long-run cost function and the three selected cost share equations as a multivariate regression system. Resulting in more efficient parameter estimates than would be obtained by applying OLS estimation to each model, including the cost share equations in the estimation procedure has the effect of adding many additional degrees of freedom without adding any unrestricted regression coefficients (Christensen and Greene 1976).

Efficacy of six models in describing the Canadian sawmilling industry's production technology was tested. The models are the unrestricted TL form cost function (Model I), Hicks neutrality (Model II), no technical change (Model III), homotheticity (Model IV), homogeneity (Model V), and unitary elasticity (Model VI). The empirical results of each model are summarized in Table 6.1, followed by the meaning and significance of disembodied technological progress and the procedure for selecting the best model that described the industry's production technology are discussed successively.

Table 6.1. Parameters of six-translog form cost functions estimated according to IZEF/MLE procedure for the Canadian sawmilling industry 1961-2000

Parameters	Models and their Estimated Coefficients (Asymptotic *t*-ratios in parentheses)					
	I Unrestricted TL	II Hicks-neutrality	III No Tech. Change	IV. Homo-theticity	V Homogenei-ty	VI Unitary elasticity
Const. α_0	20.620 (26.580)	23.209 (13.360)	19.029 (22.240)	20.944 (25.960)	21.024 (27.900)	16.698 (256.100)
Output: γ_Q	1.089 (4.962)***	1.681 (7.810)***	1.496 (18.070)***	0.287 (2.158)**	0.267 (2.412)**	0.398 (1.720)
Labor β_L	-0.881 (-5.948)***	-1.065 (-3.775)***	-0.615 (-4.159)***	-0.974 (-6.172)***	-0.988 (-6.562)***	0.501 (58.100)***
Capital β_K	0.144 (1.218)	0.908 (2.832)**	-0.060 (-0.444)	0.118 (0.977)	0.127 (1.112)	0.125 (23.760)***
Energy β_E	-0.075 (-1.810)	-0.061 (-0.260)	-0.142 (-3.390)***	-0.0569 (-1.367)	-0.054 (-1.344)	0.013 (8.655)***
Material, β_M	1.812 (15.920)***	1.219 (4.216)***	1.817 (17.150)***	1.913 (14.770)***	1.915 (14.730)***	0.361 (32.700)***
Time, θ_T	0.022 (2.322)**	-0.005 (-0.687)	------	0.038 (3.077)***	0.038 (3.174)***	0.075 (8.211)***
β_{LL}	0.196 (12.620)***	0.191 (7.116)***	0.173 (12.440)***	0.207 (12.170)***	0.208 (12.560)***	------
β_{KK}	0.025 (2.060)**	0.103 (2.463)**	0.006 (0.421)	0.018 (1.834)	0.022 (1.889)	------
β_{EE}	0.014 (4.735)***	0.019 (0.653)	0.011 (3.568)***	0.014 (5.227)***	0.014 (5.162)***	------
β_{MM}	0.223 (12.700)***	0.217 (3.819)***	0.216 (15.340)***	0.226 (13.080)***	0.225 (13.050)***	------
γ_{QQ}	0.134 (0.263)	2.223 (2.790)	-0.119 (-3.220)***	-0.229 (-0.422)	------	------
θ_{TT}	-0.001 (-1.123)	0.004 (3.284)	------	-0.002 (-1.776)	-0.001 (-3.956)***	-------
β_{LK}	0.004 (0.363)	-0.046 (-1.860)	0.018 (1.733)	0.005 (0.508)	0.004 (0.431)	--------
β_{LE}	0.008 (2.059)**	0.011 (0.572)	0.014 (4.230)***	0.005 (1.251)	0.005 (1.226)	---------
β_{LM}	-0.208 (-15.470)***	-0.156 (-5.351)***	-0.205 (-19.850)***	-0.217 (-14.470)***	-0.217 (-14.440)***	--------

Table 6.1 (cont'd). Parameters of six-translog form cost functions estimated according to IZEF/MLE procedure for the Canadian sawmilling industry 1961-2000

Para-meter	I Unrestrict-ed TL	II Hicks-neutrality	III No Tech. Change	IV. Homo-theticity	V Homogenei-ty	VI Unitary elasticity
β_{KE}	-0.018 (-4.655)***	-0.013 (-0.531)**	-0.019 (-4.481)***	-0.019 (-4.991)***	-0.018 (-5.007)***	------
β_{KM}	-0.011 (-1.023)	-0.044 (-1.325)**	-0.005 (-0.435)	-0.008 (-0.797)	-0.008 (-0.743)	------
β_{EM}	-0.005 (-1.279)	-0.017 (-0.554)**	-0.006 (-1.671)	-0.000 (-0.101)	-0.000 (-0.108)	------
θ_{LT}	0.000 (0.072)	------	------	-0.001 (-0.899)	-0.002 (-0.909)	-0.009 (-7.087)***
θ_{KT}	0.000 (0.298)	-------	-------	0.001 (1.626)	0.001 (1.601)	0.001 (1.242)
θ_{ET}	-0.000 (-0.356)	-------	-------	-0.000 (-0.050)	-0.000 (-0.048)	-0.000 (-0.315)
θ_{MT}	-0.000 (-0.204)	--------	---------	-0.000 (-0.112)	-0.000 (-0.083)	0.008 (5.015)***
γ_{LQ}	-0.110 (-3.931)***	-0.132 (-8.529)***	-0.109 (-12.880)***	------	------	0.026 (0.771)
γ_{KQ}	0.010 (1.706)	0.016 (0.943)	0.006 (0.856)	-------	------	-0.026 (-1.239)
γ_{EQ}	0.004 (0.238)	0.010 (0.707)	0.009 (4.670)	--------	------	0.009 (1.535)
γ_{MQ}	0.096 (4.700)***	0.106 (3.835)***	0.095 (12.650)***	--------	------	-0.009 (-0.223)
θ_{QT}	0.003 (0.125)	-0.096 (-3.039)	---	0.018 (0.846)	0.009 (2.554)**	-0.006 (-6.739)***
Restri-ctions	None	3	6	3	4	6
Log of likelihood function	525.590	492.923	518.213	523.815	523.736	482.058
Calculated χ^2	-----	65.334	14.754	3.550	3.708	87.064
Critical χ^2	------	7.81	12.59	7.81	9.49	12.59

Note: *** and ** indicate statistical significance at the 1% and 5% levels, respectively.

Disembodied Technological Progress: First, a brief on each model's result of disembodied technological progress is in order. Disembodied technological progress is revealed through the coefficient on the time trend variable (T), which is included in models I, II, IV, V, and VI. Thus, according to the asymptotic t-ratios of the coefficient on T, each of models I, IV, V and VI has the capability of capturing statistically significant 2.2%, 3.8%, 3.8%, and 7.5% average annual rates of disembodied technological progress over the study period, respectively (Table 6.1).

The 2.2% average annual rate of disembodied technological progress is consistent with the 2% growth rate of the "residual" TFP, which was generated with the application of the multilateral index model of the nonparametric method (Table 5.5). This is an encouraging outcome, which verifies credibility of the data, robustness of the results, and scientific merit of the two methods.

Model Selection Procedure: Model II results show that the Hicks-neutrality null hypothesis is rejected at the 5% level of significance in accordance with the log likelihood ratio (LR) test (Table 6.1). Furthermore, the LR test statistics show that neither the no technological change hypothesis (Model III) nor the unitary elasticity hypothesis (Model VI) can be accepted at the 5% significance level. Obviously, rejection of the no technological change hypothesis suggests presence of technological change over the study period, while rejection of the unitary elasticity hypothesis means that a Cobb Douglas functional form cannot describe the industry's production technology.

In contrast, neither the null hypothesis on homotheticity (Model IV) nor that on homogeneity (Model V) can be rejected. These results indicate that either a homothetic or homogeneous model can describe the Canadian sawmilling industry's production technology. Nautiyal and Singh (1985) reached at the same conclusion. They stated that the production structure of the "Canadian lumber industry" was homothetic and homogeneous.

The outcome that a homothetic technology characterized the Canadian sawmilling industry over the study period is encouraging, as it shows that both the input price ratios and the output level determined cost minimizing input combinations. This verifies specification of the industry's total production cost as a function of input prices and output level.

The LR test results reveal that the Canadian sawmilling industry's production technology was characterized by disembodied technological progress and by homotheticity and homogeneity. Hence, the most appropriate model is one characterized by disembodied technological change, statistically significant technological change, homotheticity, and homogeneity.

The objectives of this study, however, involve investigation of the dynamics of various technological attributes. Thus, Model I, the nonhomothetic, unrestricted TL form long-run cost function, was selected as the one that meets the objectives. This decision to select Model I is based on two main reasons. Firstly, it is a "full technology model" (Stevenson 1980). In other words, it is a model with sufficient information necessary for conducting complete analysis of the production technology. Secondly, the results of Model I (Table 6.1) show that all of the estimated coefficients, which are required for computing the various measures of technological attributes: factor substitution elasticities, price elasticities of derived demand for inputs, economies of scale, elasticity of cost with respect to output, TFP growth, and cost diminution rate, are statistically different from zero.

Economic theory also suggests that a cost function is well behaved if it is concave in input prices and if its input demand functions are strictly positive. The TL form long-run cost function does not satisfy these globally (Berndt and Wood 1975). Hence, it was necessary to check the fitted TL cost function for positivity and concavity. Positivity is satisfied, if the fitted cost shares are positive. Tests of the fitted cost shares, which are input demand functions, revealed that the positivity conditions were satisfied at each annual observation. Concavity of the TL long-run cost function is satisfied, if the Hessian matrix of the second-order partial derivatives is symmetric and negative semidefinite (Varian 1984). While the Hessian is symmetric by assumption, its negative semidefiniteness was checked for each annual observation and mean values; and was found to be true.

Finally, the TL form long-run total cost function, Model I, which characterizes the Canadian sawmilling industry's production technology as a nonhomothetic, is consistent with the objectives of this study and with economic theory requirements. The following technological attributes of the industry are, therefore, analyzed using the estimated parameters of that model.

6.2 SUBSTITUTION AND PRICE ELASTICITIES

6.2.1 Factor Substitution Elasticities

Equations (3.36) and (3.37) were used to calculate the AES results that are reported in Table 6.2, while equations (3.38) and (3.39) were used to calculate MES that are reported in Table 6.3. Because both are easily influenced by the magnitude of a given input cost shares over the study period, they were calculated at the mean value of input cost shares over the entire sample.

Major previous studies (e.g., Berndt and Wood 1975; Pindyck 1979; Nautiyal and Singh 1985; Singh and Nautiyal 1986; and Kant and Nautiyal 1997) used AES to analyze degrees of technical substitutability between pairs of inputs. For the reasons discussed earlier, this study also focuses more on AES results than on MES.

Table 6.2. AES estimates for the Canadian sawmilling industry (standard errors in parentheses): 1961-2000

Input i	*Input j*			
	Labor	Capital	Energy	Material
Labor	**-0.236** (0.139)	1.091 (0.250)***	2.183 (0.574)***	-0.189 (0.077)**
Capital		**-5.508** (0.797)***	-6.104 (1.526)***	0.831 (0.165)***
Energy			**-13.847** (7.327***	0.573 (0.333)
	Symmetric			
Material				**-0.096** (0.064)

Notes: *** and ** indicate significance at the 1% and 5% levels, respectively.

In accordance with economic theory, the own-partial elasticities of substitution are all negative (Table 6.2). The AES results reveal that between the pairs of labor/capital, labor/energy, capital/ material, and energy/ material are positive, suggesting that these input pairs were substitutes to each other. On the other hand, the AES between the pairs of labor/ material and capital/energy are negative, implying complementarities between these in pairs (Table 6.2).

The substitution elasticities of the labor/capital and labor/energy input pairs are greater than unity, implying that it was relatively easy for the industry to substitute labor for capital and energy. Moreover, statistically significant degrees of substitutability between labor/capital (1.091) and labor/energy (2.183) as well as the significant complementarities between labor/ material (-0.189) and capital/energy (-6.104) were possible over the study period (Table 6.2). The own-elasticities of substitution of labor and Material are less than unity and are statistically not different from zero, suggesting that demand for these inputs was not responsive to either their marginal productivity ratio or to their price ratio.

These findings are also consistent with economic theory in that productive inputs are expected to be "neither perfect substitutes nor perfect complements" (Sherif 1983). Moreover, AES findings of other studies were more or less the same as those of this study. For example, Martinello (1985) found all other pairs of inputs to be substitutes, with the exception of Material and energy; Nautiyal and Singh (1985) and Singh and Nautiyal (1986) found labor/capital; labor/energy; and labor/ material to be substitutes; Kant and Nautiyal (1997) found pairs of all four inputs, i.e., capital, labor, energy, and Material, to be substitutes.

The magnitudes of σ_{KK} and σ_{EE}, which are -5.508 and -3.847, respectively, might appear to the casual reader to be unrealistically high (Table 6.2). But, these results are consistent with findings of several other researchers, who conducted empirical research on manufacturing industries and other sectors, using the method used in this study. For example, Binswanger (1974c) found -26.573 for fertilizer in the U.S. agricultural sector; Berndt and Wood (1975) reported -10.66 for energy in the U.S. manufacturing sector; and Pindyck (1979) reported -16.96 and -27.21 for the energy sector in the national economies of Canada and the U.S., respectively.

Table 6.3. MES estimates for the Canadian sawmilling industry (standard errors in parentheses): 1961-2000

	Input j			
Input i	Labor	Capital	Energy	Material
Labor	n.a.	0.443 (0.115)***	0.807 (0.205)***	0.205 (0.067)***
Capital	0.809 (0.118)***	n.a.	-0.073 (0.221)	0.778 (0.110)***
Energy	0.324 (0.152)**	0.156 (0.169)**	n.a.	0.291 (0.149)
Material	-0.488 (0.069)***	0.485 (0.110)***	0.351 (0.069)***	n.a.

Notes: (i) *** and ** indicate significance at the 1% and 5% levels, respectively.
(ii) n.a. means not applicable.

According to the MES results, the pairs of capital/energy and material/labor are complements; and all other input pairs are substitutes (Table 6.3). This is in contrast to the AES results (Table 6.2). Thus, there are technically inherent features that characterize the difference between AES and MES. The main difference between the two is that AES is always symmetric (e.g., $\sigma_{KL} = \sigma_{LK}$) (Table 6.2). MES does not meet this condition. Moreover, MES does not provide own-substitution elasticities, as AES does. However, Blackorby and Russell (1989) argue that for more than two inputs, the MES is symmetric, if and only if, the inputs converge to the same constant, in which case the production function is a member of the implicit CES-Cobb-Douglas family. In any case, as pointed out earlier, in this study conclusions are based on the AES results.

6.2.2 Own- and Cross-Price Elasticities

The negative values of own elasticities of substitution, σ_{ii}, (Table 6.2) and of the own-price elasticities of demand, ε_{ii}, (Table 6.4) reveal that the necessary condition for global concavity of the dual cost function is met (Berndt 1991).

Table 6.4. Estimated own- and cross-price elasticities of demand for inputs in the Canadian sawmilling industry (standard errors in parentheses): 1961-2000

	Input j (= L, K, E, M) Prices			
Input i	Labor	Capital	Energy	Material
Labor	**-0.079** (0.046)	0.134 (0.031)***	0.044 (0.011)***	-0.099 (0.040)
Capital	0.364 (0.083)***	**-0.676** (0.098)***	-0.123 (0.031)**	0.435 0.086)***
Energy	0.728 (0.192)***	-0.749 (0.187)***	**-0.270** (0.148)**	0.300 (0.175)
Material	-0.063 (0.026)	0.102 (0.020)***	0.012 (0.007)	**-0.050** (0.034)

Note: *** and ** indicate significance at the 1% and 5% levels, respectively.

Although most of the estimates are statistically significant, both the own- and the cross-price demand elasticities are inelastic (Table 6.4). The cross-price elasticities between the pairs of capital/energy and energy/capital show complementarities; while the pairs of labor/capital, labor/energy, capital/labor, capital/material, energy/labor, and material/capital were substitutes (Table 6.4). These results are consistent with those observed in many previous studies of the sawmilling industry (e.g., Banskota et al. 1985; Nautiyal and Singh 1985; Martinello 1985; Singh and Nautiyal 1986; Meil et al. 1988; Puttock and Prescott 1992).

The highly inelastic nature of the own- and the cross price elasticities indicates that each input was treated as a "basic" good during the study period. In other words, the Canadian sawmilling industry experienced very limited possibilities for substituting one input for another (Table 6.2). It is believed that this condition is one of the sources of inefficiency in the industry's production line.

6.3 DECOMPOSED TFP GROWTH AND OTHER ATTRIBUTES

In this section, decomposition of TFP into its main determinants and the nature of several technological attributes are summarized in Table 6.5, followed by interpretive discussions on the major attributes: elasticity of total cost with respect to output, scale effects, technological progress, TFP growth, returns to scale, and economies of scale.

Table 6.5. Average annual results of key technological attributes at ten- and forty-year intervals for the Canadian sawmilling industry

Period	ε_{CQ} from Eqn. **(3.34)**	*Scale effects:* $(1-\varepsilon_{CQ})\dot{Q}$ from Eqn. **(3.32)**	Technological progress ε_{CT} from Eqn.**(3.26)**	*TFP growth:* $(1-\varepsilon_{CQ})\dot{Q}-\varepsilon_{CT}$ from Eqn. **(3.32)**	*Returns to scale*: $1/\varepsilon_{CQ}$ from Eqn. **(3.33)**	Economies of scale: $1-\varepsilon_{CQ}$ from Eqn.**(3.35)**
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1961-70	0.230	0.041	-0.021	0.062	*4.356*	*0.770*
1971-80	0.231	0.051	-0.023	0.074	*4.324*	*0.769*
1981-90	0.245	0.022	-0.023	0.045	*4.087*	*0.755*
1991-00	0.292	0.024	-0.024	0.048	*3.422*	*0.708*
1961-00	0.249	0.034	-0.023	0.057	4.017	*0.751*

Note: First the logarithmic mean values of the input prices and of the aggregate output quantity that appear in the right hand side of the identified formulas were computed for each interval period. Then, these mean values were multiplied by their respective coefficients from Model I (Table 6.1).

Interpretations and implications of the technological attributes summarized in Table 6.5 are as follows:

Elasticity of Total Cost

The elasticity of total cost with respect to output, ε_{CQ}, [Column (2)] is a measure of the degree of responsiveness of total cost to changes in total output, is positive as one would expect. That is, the higher the output the higher the production cost.

ε_{CQ} plays important role in characterizing the production technology: if the production function exhibits increasing returns to scale (IRTS), then $\varepsilon_{CQ} < 1$, implying that doubling of output would less than double total cost under given input prices; if the production technology experiences constant returns to scale (CRTS), then ε_{CQ} = 1, suggesting that doubling output would equiproportionately double total cost given that input prices remain unchanged; and, finally, if the production technology exhibits decreasing returns to scale (DRTS), then $\varepsilon_{CQ} > 1$, hence, doubling output would more than double total cost under given input prices.

Results for all the ten- and forty-year interval periods reveal that total cost was inelastic (Table 6.5). That means production cost responded to increases in output at a slower rate, implying IRTS. For example, a 1% rise in aggregate average annual output over the study period would have resulted in only 0.25% rise in total cost, *ceteris paribus*.

Scale Effects

The scale effects (SCEs), [Column (3)] are products of economies of scale and the average annual growth rate of the aggregate output. Given that the industry's technology was characterized by IRTS, the positive nature of these results is as should be expected. These results contribute to TFP growth [Column (5)]. The average annual SCEs were 3.4% over the study period.

Technological Progress

Technological progress [Column (4)] is inferred through the rate of cost diminution, which is also referred to as the dual measure of the primal TFP growth under fixed input prices and output quantity (Berndt and Watkins 1981). Consistent with the theoretical concept, the results are all negative. Over the study period, for example, the average annual cost diminution rate was 2.3%. That is, technical progress did indeed contribute to TFP growth.

Growth in TFP

The TFP growth results comprise effects of mutually reinforcing two important factors: scale effects and cost diminution rate. Thus, the relatively high average annual growth rate of 5.7% over the study period is a joint effect of the two factors (Table 6.5). This result is more than double of the approximately 2.0% growth rate, which was generated with the nonparametric, multilateral index procedure (Table 5.5).

Overall, parametric results show that the industry gained measurable TFP growth in the 1960s and in the 1970s, with average annual rates of 6.2% and 7.4%, respectively [Column (5)]. However, there were slowdowns in the 1980s and 1990s, with the ten-year interval average annual growth rates being 4.5% and 4.8%, respectively.

Returns to Scale

Returns to scale (RTS) [Column (6)] are inversely related to the elasticity of cost with respect to output. That is, the lower the elasticity of cost the higher the RTS. As highlighted earlier, the consistently greater than unity results verify that the industry gained IRTS over the study period.

Economies of Scale

Economies of scale [Column (7)] indicate a declining range of a long-run average cost, resulting from expanded level of output. Economic theory suggests that there are internal and external economies. Internal economies are attributed to expansion of a firm's production operations through technological progress, managerial improvements, risk spreading or combination of two or all three factors (Pearce 1992). External economies arise from the expansion of industrial operations through various actions that include acquisitions and mergers.

Following Christensen and Greene (1976), economies of scale (ES) were calculated as unity minus ε_{CQ}. A positive value of ES implied that the industry gained economies of scale over the study period. This outcome is consistent with the above discussed less than unity ε_{CQ} results recorded for the ten- and forty-year intervals (Table 6.5). For the forty-year study period, for example, the average annual ES value was 0.751. Several other studies reached at the same conclusion (e.g., Banskota et al. 1985; Nautiyal and Singh 1985).

Table 6.6. Decomposition of the dual measure of the primal TFP growth at ten- and forty-year intervals for the Canadian sawmilling industry: 1961-2000

Period	Pure technological change (PTC)	Non-neutral technological change (NTC)	Scale-augmenting technological change (STC)	Elasticity of cost with respect to time dependent technological progress: ε_{CT}
(1)	(2)	(3)	(4)	(5)
1961-70	-0.021	0.001	-0.001	-0.021
1971-80	-0.021	0.001	-0.002	-0.023
1981-90	-0.021	0.001	-0.003	-0.023
1991-00	-0.021	0.001	-0.004	-0.024
1961-00	-0.021	0.001	-0.003	-0.023

Sources: Eqns. (3.25, (3.26), (3.27), (3.28) for PTC, NTC, and STC, respectively

PTC is expected to capture pure technological progress achieved through enhanced quality of human capital (knowledge and skills). Hence, the negative results indicate contributions of PTC to total cost diminution at an average rate of 2% per year (Table 6.6). By contrast, the positive values of NTC indicate effects of input augmenting technological changes, resulting in a 0.1% annual increase in total cost, while the scale augmenting technological changes (SCT) lead to an average annual decline of 0.3% in total cost (Table 6.6). The dual measure of the primal TFP growth, ε_{CT}, which is the sum of PTC, NTC, and STC shows an average annual rate of 2.3% diminution in total cost over the study period (Table 6.6).

Table 6.7. Average annual rates of technological change biases at ten- and forty-year intervals for the Canadian sawmilling industry: 1961-2000

Period	Capital	Labor	Energy	Material
(1)	(2)	(3)	(4)	(5)
1961-70	0.002	0.000	-0.007	0.000
1971-80	0.003	0.000	-0.005	0.000
1981-90	0.002	0.000	-0.003	0.000
1991-00	0.002	0.000	-0.005	0.000
1961-00	0.002	0.000	-0.005	0.000

Note: The formula in Eqn. (3.34) was used for the calculation.

The production technology of the Canadian sawmilling industry was characterized by capital-using, energy-saving, and Hicks-neutrality on labor and material (Table 6.7). That is, technological change resulted in rising demand for capital; declining demand for energy; and had no effect on the individual demand functions for labor and material, *ceteris paribus*.

An input bias technological change has important economic implications. For example, the technology's Hicks-neutrality on labor and material implies that technological change in the Canadian sawmilling industry used labor and material proportionately to produce an optimal output, Q^*, leaving the marginal rate of technical substitution of material for labor or *vise versa* as well as the price ratio of the two inputs fixed. That is, the isoquant moved inward (toward the origin) along the expansion path in the production process of Q^* at a least-cost combination of the two inputs.

These findings are more or less consistent with those of previous studies. For example, Martinello (1985) found technological change in the industry to be labor and round wood (material) saving and capital and energy using. Stier (1980, 1985) observed capital using and labor saving technological change bias for U.S. forest products industries.

6.4 COMPARISON WITH PREVIOUS STUDIES

In this section, empirical findings for key technological attributes from this study and other selected studies that were conducted on the Canadian and American sawmilling/lumber industries are summarized and evaluated. The extent to which each study has been cited in the literature and methodological similarity with this study were the main criteria for selecting the studies.

A caveat on the consequences of comparing empirical results from different studies is instructive. Different studies must not be compared literally, based on the face values of parametric coefficients. Doing so is misleading and, in most cases, confusing, because of possible differences in the following and other conditions: (i) data structures, (ii) sample size (e.g., length of time period), (iii) regional and international variations in social, economic, industrial, and environmental policy instruments, (iv) accessibility to and structure of markets, and (v) efficiency and effectiveness of raw material delivery and utilization. These and other similar conditions are sources of incomparability of industrial- empirical studies (Ghebremichael et al. 1990, Ghebremichael and Nanang 2004).

In general terms, there are "scientific requirements" every empirical econometric model must meet to be validated. Although there is no "magic formula" for selecting the most effective and efficient econometric model, there are "alternative general philosophies" that can be used successfully (Myers 2004). The following five statistical criteria for selecting an effective econometric model are commonly considered as necessary: *parsimony*: other things being equal the simplest model could be the best; *identifiability*: whether numerical estimates of the parameters of a structural equation can be obtained from the estimated reduced-form coefficients, i.e., the endogenous and exogenous variables are identified correctly during the process of building an econometric model; *statistical adequacy*: effective and efficient explanatory power; (iv) *consistency* with social, biological, and physical theories; and *predictive power*:: how far apart the predicted values based on estimated parameters are from the actual data (Gujarati 2003; Myers 2004).

Thus, the selected previous studies and this study have to be evaluated in light of these statistical criteria as well as the relevance of each study's results for policy making; not on the basis of "face values" of estimated parameters. For the purpose of this section, the following three common categories of research findings are selected: input substitution elasticities, price elasticities of derived demand for inputs, and growth in TFP.

The information is classified into two parts. First, each study is characterized by author and publication year, model specification, functional form, and sample size (Table 6.8). Then, each study's empirical findings on the basis of the above-identified parameters are summarized in the five tables that follow Table 6.8.

Table 6.8. Methodological summaries of this study and selected studies conducted on Canadian and American sawmilling industries

Author(s) (year)	Model specification	Functional form	Sample range
Nautiyal and Singh (1985)	Long-run cost function: $C = f(Q, W_K, W_L, W_E, W_M; T)$	Translog	1965-81
Martinello (1985)	Long-run cost function: $C = f(Q, W_K, W_L, W_E, W_M; T)$	Translog	1963-82
Banskota et al. (1985)	Total cost function for cross-sectional data:: $C = f(Q, W_K, W_L, W_E, W_M)$	Translog	1978 cross-sectional
Singh and Nautiyal (1986)	Long-run total cost function: $C = f(Q, W_K, W_L, W_E, W_M; T)$	Translog	1955-1982
Stier (1980)	Restricted (two exogs. variables) cost function: $C = f(Q, W_K, W_L; T)$	Translog	1958-74
Abt (1987)	Variable (short-run) cost function: $VC = f(Q, K, W_L, W_M; T)$	Translog	1963-78 pooled data
Puttock and Prescott (1992)	Variable (short-run) cost function: $VC = f(Q, K, W_L, W_E, W_M)$	Translog	1980-84 pooled data
This study	Long-run cost function: $C_t = g_t(Q_t, W_{Kt}, W_{Lt}, W_{Et}, W_{Mt}; T)$	Translog	1961-00

The following five tables show discrepancies among the seven selected previous studies in reporting the required parametric results. Examining each study's model specification reveals that database structural limitations were the sources of the discrepancies (Table 6.8). In contrast, this study reports all the required parameters. For example, only Nautiyal and Singh (1985) and Singh and Nautiyal (1986) reported partial own-Allen elasticities of input substitution (Table 6.9).

Table 6.9. Allen partial own-elasticities (AES) of input substitution from this study and from two selected studies

Author(s)/study year	σ_{LL}	σ_{KK}	σ_{EE}	σ_{MM}
Nautiyal and Singh (1985)	-1.95	-8.61	-13.40	-0.88
Singh and Nautiyal (1986)	-3.29	-2.14	-10.56	-0.16
This study	-0.24	-5.51	-13.85	-0.10

Table 6.10. AES cross-elasticities of input substitution from this study and from four selected studies

Author(s)/study year	σ_{LK}	σ_{LE}	σ_{LM}	σ_{KE}	σ_{KM}	σ_{EM}
Nautiyal and Singh (1985)	0.93	0.49	0.60	3.56	1.24	1.36
Martinello (1985)	0.23	1.36	0.00	0.04	0.58	1.93
Banskota et al. (1985)	1.73	1.35	0.06	1.97	-0.05	0.78
Singh and Nautiyal (1986)	2.58	4.49	0.24	-0.40	-0.62	-0.02
This study	1.09	2.18	-0.19	-6.10	0.83	0.57

Table 6. 11. Own-price elasticities of derived demand for inputs from this study and from six selected studies

Author(s)/study year	ε_{LL}	ε_{KK}	ε_{EE}	ε_{MM}
Nautiyal and Singh (1985)	-0.48	-1.21	-1.32	-0.44
Martinello (1985)	-0.24	-0.30	-1.12	-0.37
Banskota et al. (1985)	-0.36	-0.76	-0.07	-1.09
Singh and Nautiyal (1986)	-0.86	-0.24	-1.04	-0.69
Puttock and Prescott (1992)	-0.49	n.r.	-2.20	-0.20
Abt (1987), U.S. Western region	-0.39	n.r.	n.r.	-0.20
This study	-0.08	-0.68	-0.27	-0.05

Table 6. 12. Cross-price elasticities of derived demand for inputs from this study and from five selected studies

Author(s)/study year	ε_{LK}	ε_{LE}	ε_{LM}	ε_{KE}	ε_{KM}	ε_{EM}
Nautiyal and Singh (1985)	0.13	0.05	0.03	0.34	0.63	0.69
Martinello (1985)	0.03	0.21	0.00	0.01	0.24	0.81
Banskota et al. (1985)	0.63	0.49	0.02	0.27	-0.01	0.06
Singh and Nautiyal (1986)	0.29	0.44	0.13	-0.04	-0.33	-0.01
Abt (1987)	0.01	n.r.	0.39	n.r.	-0.19	n.r.
This study	0.13	0.04	-0.09	-0.12	0.44	0.03

Table 6.13. TFP growth from this and from a selected study

Author(s) (year)	TFP growth (%)
Martinello (1985)	4.3
This study	5.7

Although all of the studies estimated TL form cost functions, the above five tables of results show that they differ in several ways. Their differences include model specification details. For example, Stier (1980) specified the production technology as a function of capital and labor only, while Abt (1987) specified it as a function of capital, labor, and material only. Moreover, Abt (1987) and Puttock and Prescott (1992) estimated restrictive variable cost functions. Consequently, these researchers were unable to analyze the important technological attributes, such as price elasticity of derived demand for an input, Allen elasticity of factor substitution, and TFP growth. The missing parameters are crucial for characterizing an industry's production technology, which is the ultimate goal of such studies.

In terms of model specification, Nautiyal and Singh (1985), Martinello (1985), and Singh and Nautiyal (1986) are similar to that of this study. But, they also differ from this study and among themselves in analytical depth. For example, Martinello (1985) did not report AES, but reported TFP growth. Nautiyal and Singh (1985) and Singh and Nautiyal (1986) reported results on AES, but did not report TFP results.

By comparison, this study possesses features that establish its uniqueness. They include the following: (i) coverage of a longer time frame (statistically sufficient sample size); (ii) generation of capital rental price, using the perpetual inventory method, a methodology that accounts for opportunity cost of various capital assets, such as machinery and equipment); (ii) a database structure that details the multioutput and multiinput nature of the Canadian sawmilling industry; and (iv) the scope of the empirical work, which involves implementation of two major methods, generating a range of nonparametric and parametric empirical results.

CHAPTER 7 SUMMARY OF THE FINDINGS

This chapter summarizes the two methods and their respective findings. It was in accordance with recommendations made in the rapidly growing literature that the two major empirical methods were jointly implemented in this study. The methods are the nonparametric method, which involved application of the multilateral index procedure; and the parametric method, which involved simultaneous estimation of a multivariate regression system of translog form long-run cost function and three out of four cost share equations that are nested to the long-run cost function. Sections 7.1 and 7.2 summarize the nonparametric and parametric methods and results, respectively.

7.1 THE NONPARAMETRIC METHOD AND RESULTS

7.1.1 The Method

Productivity is considered as the core of the science of economics. It is one of the main engines of economic growth. Researchers attribute the historically observed increases in capital formation to productivity growth.

There are two forms of productivity: partial factor productivity (PFP) and total factor productivity (TFP). PFP is real-aggregate output per unit of a given input quantity (e.g., labor), while TFP is real-aggregate output per unit of real-aggregate input. Although public and private agencies, such as Statistics Canada and the U.S. Bureau of Labor Statistics, analyze and record PFPs – particularly partial productivity of labor, it has neither scientific nor practical merits, because output is a function of all inputs and technological change. Hence, the main focus of this study was on the levels and growth rates of TFP.

Growth in TFP is the difference between the growth in revenue-share weighted real-aggregate output and the growth in cost-share weighted real-aggregate input. For the purpose of this study, TFP growth is an indicator of technical improvements and technological progress over the study period.

Measurement and interpretation of the dynamics of TFP require a clear understanding of many complex factors that influence it. They include R&D expenditures, inventions, innovations, the rate of technological diffusion, institutional arrangements, nature and effectiveness of organizations, societal preferences, natural resource endowment, market demand and supply conditions, and relationship between labor and management.

Thus, the various terms used to define TFP reveal the challenges to measure and analyze it and the lack of universally accepted scientific definition for it. The labels frequently placed on TFP include "a residual", "a measure of our ignorance", "Manna from Heaven", and a measure of "supernormal returns" to investing in R&D – returns that exceed the full opportunity cost of an investment.

In addition to the application of the multilateral index procedure, using the original data, to measure and analyze the PFPs and TFP, two supplementary analyses were conducted. The first involved regression of the gross TFP on output and a time dependent technological variable, while the second dealt with the application of the multilateral index procedure to simulate effects of raising capital cost allowance (CCA) and investment tax credit (ITC) and reducing corporate income tax (ITC) on capital formation and on TFP growth.

7.1.2 The Results

First, historical trends in the data are summarized. Then, results *without* the changes in taxation are discussed, followed by a discussion on the effects of the changes in the tax rates.

Historical Trends in the Data

The first step in applying the multilateral index model to analyze TFP is to examine closely the trends in the input cost shares in total cost and output shares in total revenue, the aggregate quantity of inputs and aggregate quantity of outputs, and the prices of inputs and outputs.

Although researchers often overlook this step, close examination of the key variables' behavior over time is crucial as it reveals anomalies in the data. This allows the researcher to take remedial measures; it enhances the credibility and scope of the findings; and it provides useful insights into the dynamics of the technological attributes being analyzed.

On average, aggregate output rose at a faster rate than aggregate input over the forty-year study period (1961-00). This gave a clear indication that the industry attained measurable TFP. For example, during the 1960s, the output quantity grew at an average annual rate of 5%, while the aggregate input quantity increased at a rate of 3%. The average annual growth rates over the study period also showed similar trends of 5% and 3% for aggregate output and aggregate input, respectively.

Average annual shares in total cost varied by type of input: the share of capital remained nearly constant, within the range of 8%, while that of labor declined substantially from more than 46% in the 1960s to 21% in the 1990s, a very important preliminary indicator of a labor-saving production technology. The share of energy remained steady, within the range of 2%. The share of raw material (sawlogs) accounted for the largest share and jumped from 43% in the 1960s to 69% in the 1990s. These results suggest that targeting raw material for cost minimization would have been advisable for the industry.

Similarly, the output shares in total revenue revealed that lumber is the dominant product of the Canadian sawmilling industry. It accounted for average annual of more than 80% of the total revenue over the study period. The share of wood residues (wood chips) ranged between 12% and 19%, while that of shakes and shingles was roughly 1%.

Partial Factor Productivities

Partial factor productivities (PFPs) of capital (PPK), labor (PPL), energy (PPE) and Material (PPM), were analyzed. All PFPs trended upward, iindicating that either use of each input declined steadily or the industry had experienced technical and/or technological improvements over the study period. The ten-year interval average annual growth rate of PPK ranged between 3% and 4%; that of PPL between 3% and 5%; that of PPE between 1% and 5%; and that of PPM between 2% and 3%.

Total Factor Productivity

When the multilateral index model is used, growth in total factor productivity (TFP) is the difference between the revenue-share weighted output quantity growth rates and the cost-share weighted input quantities. Overall, TFP followed upward trends in output and input quantities over the forty-year study period. The average annual growth rate of TFP over the study period was 2.0%. However, rapid annual fluctuations were observed.

Output and Time Dependent Technology as Sources of TFP Growth

Output expansion and technological progress are commonly identified as major sources of TFP growth. To examine their effects, two regression models were estimated. The first model used the quadratic form in output, while the second used the natural log of output and time trend variable. The GLS method with the Cochrane-Orcutt iterative estimation procedure was used in order to minimize the potential problem of autocorrelation.

Overall, both models performed reasonably well. The estimated coefficients were highly significant, except for the constant in Model 2; and their signs met the hypotheses that were set forth in accordance with economic theory (Table 5.6). The R^2 of each model was more than 98%; and the Durbin-Watson (DW) statistics were 1.632 and 1.795 for Models 1 and 2, respectively.

According to the results of the first model, the marginal effect of increasing aggregate output on TFP growth was more than 44%, *ceteris paribus*. But, the coefficient on Q^2 was -0.0353, indicating TFP rose (accelerated) with output at a declining rate of 3.5%.

In the second model, the coefficient on lnQ (= natural log of aggregate output) was interpreted as an elasticity of TFP with respect to Q. For example, a 1% increase in Q would generate approximately 0.3% average annual growth in TFP, *ceteris paribus*. The coefficient on T, on the other hand, indicated that the marginal effect of technological progress on TFP growth. It showed that the average annual TFP growth rate was 0.62% over the study period.

Effects of Changes in Taxation Policy Instruments

The analysis of effects of raising CCA and ITC and reducing CIT on capital formation and on TFP growth was based on the hypothesis that all three fiscal policy measures would lead to an enhanced rate of capital formation and TFP. This hypothesis was expected to be supported through three outcomes: a higher share of capital in total cost; a higher intensity of capital in the production technology; and a slightly lower gross TFP due to fixed aggregate output and inputs (labor, energy, and Material).

Since capital formation increased capital stock, which in turn raised aggregate input quantity, the *with* policy change TFP (TFP2) was expected to be slightly lower than that *without* policy change TFP (TFP1). The results are summarized as follows:

Cost Shares: Cost shares were considered as implicit measures of capital formation due to the tax incentives. As expected, capital formation rose substantially. Over the study period, the average annual share of capital in total cost *with* the changes was estimated at 12.3%, while that *without* the changes was 8.6%. This outcome suggested an enhanced capital formation.

Capital Intensity: High capital intensity was expected to indicate a production technology characterized by more machinery, and equipment; and hence, higher productivity. It was observed that capital intensity increased steadily with the changes in taxation. Over the study period, the average annual real-capital stock per worker was estimated as $15,263.70 with the changes compared to $10,402.91 without the changes.

Effects on TFP: Higher capital formation, motivated by the tax incentives, raised aggregate quantity of the inputs significantly, while the *aggregate* output and the other inputs were unchanged. As expected, TFP2 was slightly lower than TFP1. The gap between the two measures (i.e., TFP2 minus TFP1) ranged from a least average annual rate of 0.3% in the 1960s and 4.1% in the 1990s.

7.2 THE PARAMETRIC METHOD AND RESULTS

7.2.1 The Method

The parametric approach involved specification and optimization of a dual-long-run neoclassical cost function. It was assumed that solving a general optimization problem was feasible. That is, given exogenously determined output level and input prices, firms in the sawmilling industry would choose the optimal combination of the inputs of capital, labor, energy, and material, subject to the technological constraint.

There are several reasons why estimating a dual-long-run cost function was considered more effective than estimating a production function. Firstly, there is no serious problem of multicollinearity among input prices as there is among input quantities. Secondly, government policy measures regarding timber harvesting (e.g., the annual allowable harvest rate restrictions imposed by the provinces) are very likely to lead to situations where exogenous forces determine output levels. Thirdly, since firms in the sawmilling industry compete with other firms in the economy for the same inputs, output levels and input prices are exogenously determined. Fourthly, recent developments in duality theory have enhanced the appeal of the cost function estimation approach. Fifthly, effective functional forms, such as the translog (TL) and the generalized Leontief (GL) that meet theoretical requirements for estimating cost functions have been developed and verified over the years.

In addition to their ability to represent very general production functions, the commonly used functional forms, such as the TL form, enable the researcher to compute several parameters that characterize a given production technology. The TL functional form has been found to be more reliable than the other forms in providing a credible approximation of a given technology. It has two important advantageous properties over other forms: in that it places no *a priori* restrictions on substitution possibilities among all the factors of production and it allows scale economies to vary with the level of output. Accordingly, the TL functional form was used in this study.

To ensure maximum efficiency, a multivariate regression system of four equations that included the unrestricted TL total cost function and three of the four input cost share equations was estimated, applying the IZEF/MLE. By imposing required restrictions on the long-run TL form cost function, six models were tested for their capability to describe the Canadian sawmilling industry's production technology. Model I was the unrestricted long-run TL cost function. The restricted-test ones were Model II for Hicks-neutrality of technological change, Model III for presence of technological change, Model IV for homotheticity, Model V for homogeneity, and Model VI for unitary elasticity.

The six models in the multivariate regression system were estimated simultaneously. The likelihood ratio (LR) test procedure, which does not utilize least squares and does not rely on the normality of the error term, was used to test the specified theoretical restrictions. Based on the results of the LR tests and the objectives of the study, Model I, which possesses relatively full technological information, was selected as the model capable of describing the Canadian sawmilling industry's production technology.

The estimated parameters of Model I were used to analyze several technological attributes that include the elasticities of input substitution, the own- and cross-price elasticities of derived demand for inputs, the elasticity of total cost with respect to output, scale effects, the dual measure of TFP growth in the absence of scale effects, TFP growth in the presence of scale effects, returns to scale, economies of scale, and technological change biases.

7.2.2 The Results

Input Substitution Elasticities

The degree of substitutability among all factors of production has far reaching economic implications. Generally, the purpose of the production function is to describe the substitution possibilities among inputs so that a least-cost combination of inputs is attained to produce a given level of output most efficiently.

Because, the Allen elasticity of substitution (AES) has been found to be more credible than the Morishima elasticity of substitution (MES), only the AES results are summarized here. The estimates of AES revealed that the pairs of labor/capital (1.091), labor/energy (2.183), and capital/ material (0.831) were substitutes to each other. In contrast, labor/material (-0.189) and capital/energy (-6.104) were complements. Notice that substitution of labor for capital and labor for energy were relatively easier than any other input pairs; and there were significant complementarities between labor/ material and capital/energy.

Moreover, it was observed that the own-elasticities of substitution of labor and material were less than one and were statistically not different from zero. This results suggest that demands for these inputs were not responsive to either their marginal productivity ratio or to their price ratio. In short, the AES findings made logical and economic sense, because productive inputs were expected to be "neither perfect substitutes nor perfect complements".

Price Elasticities of Derived Demand for Inputs

The cost-minimizing, optimal-derived demand for the i^{th} input is a function of all inputs that characterize the dual-long-run cost function, the prevailing coordination structure of the production technology, the level of output, the prices of all inputs, and the state of prevailing technology.

The own-price elasticities were inelastic, with values of -0.079, -0.676, -0.270, and -0.050 for labor, capital, energy, and material, respectively. The cross-price elasticity between capital and energy (-0.123) shows complementarity between these inputs. All other cross-price elasticities were positive, suggesting that those input pairs were substitutes.

The highly inelastic nature of the own- and the cross price elasticities indicated that each input was treated as a “basic” good. In effect, the low values of price elasticities suggested presence of input price “rigidity”.

Elasticity of Total Cost

To observe degree of responsiveness of total cost of production to expansion of production operations, the elasticity of total cost with respect to output, ε_{CQ}, was calculated. Its average annual rate over the study period was 0.249, indicating that the Canadian sawmilling industry’s production technology exhibited increasing returns to scale (IRTS) over the study period. For example, if the average annual of the aggregate output had increased by 1%, total cost would have increased by only 0.25%, *ceteris paribus*, implying IRTS.

Scale Effects

Scale effects were calculated as unity minus elasticity of total cost with respect to output multiplied by the rate of output growth. All ten and forty-year interval annual averages showed positive scale effects. For example, the average annual measure for the forty-year study period was 0.034. This positive value of scale effects and the inelastic nature of total production cost indicated that the industry had gained economies of scale.

The Dual Measure of the Primal TFP Growth

Change in total cost with respect to time is also referred to as the dual measure of the primal TFP growth under fixed input prices and output quantity. Equivalently, it is also referred to as cost diminution, i.e., a percentage reduction in total cost brought about by technological progress.

Consistent with the theoretical conceptions, the rates were negative. For example, over the study period, the average annual cost diminution rate was -2.3%. This result suggested that technological progress contributed to a modest average annual TFP growth.

Combined Effect of Production Scale and Cost Diminution on TFP Growth

The total of scale effects and cost diminution rate yielded TFP growth. Its growth rates in the 1960s and in the 1970s were 6.2% and 7.4%, respectively. But, there were slowdowns in the 1980s and 1990s that led to 4.5% and 4.8% rates of growth, respectively. Over the forty-year study period, the average annual growth in TFP was approximately 5.7%. These findings were consistent with the other parametric findings, such as the inelastic nature of production cost, increasing returns to scale, economies of scale, and the modest rate of cost diminution.

Returns to Scale

Returns to scale (RTS) are inversely related to the elasticity of total cost with respect to output. The lower the elasticity of cost, the higher the RTS, implying the industry gained increasing returns to scale (IRTS) over the study period. The average annual RTS for the study period was 4.02, which implied an IRTS. Generally, if elasticity of cost with respect to output is less than unity, then, doubling output should result in less than doubling of total cost; and hence, IRTS.

Economies of Scale

Theoretically, economies of scale (ES) are estimated along the expansion path, where input prices are constant and total cost is minimized. In other words, a positive ES value indicates declining range of a long-run average cost of production. In this study, unity minus elasticity of total cost with respect to output is interpreted as ES. All of the ten- and forty-year interval annual averages were positive. For example, a result of 0.751 per year over the forty-year study period revealed that the industry had gained measurable ES.

Measures and Effects of Technological Change Biases

The nature of technological change-bias has important socioeconomic implications. For example, effects of a new technology on employment and wages depend on whether the new technology is Hicks-neutral, labor-using or labor-saving. The concept of a factor-using new technology means hiring more of a given input, while a factor-saving new technology means hiring less of a given input.

At the mean value over the entire study period, the production technology of the Canadian sawmilling industry was characterized as capital-using (0.002) and energy-saving (-0.005); but as Hicks-neutral (0.000) for labor and material inputs. This outcome meant that demand for capital increased while that for energy declined over the study period, holding prices of other inputs and output constant.

In contrast, technological change did not have measurable effects on the demand for labor and material, *ceteris paribus*. That is, the Hicks-neutrality outcome means that technological change resulted in proportionate use of labor and material to produce the optimal output, leaving the marginal rate of technical substitution between these two inputs and their price ratio unchanged.

Comparison with Previous Studies

Because there is no study other than this present study that implemented the parametric and nonparametric methods jointly, only results of the previous studies that used the parametric method were compared with those of this study (Section 6.4),

Discrepancies were observed among the selected previous studies in terms of the reported empirical parameters. Structural limitations of data were the main sources of the discrepancies. Restrictive cost functions were specified for several of the selected studies. To characterize the industry's production technology, each study reported results for limited number of parameters.

By contrast, this study not only that it specified a long-run cost function and reported several parametric results, but also implemented the parametric and nonparametric methods jointly. Thus, it was possible to fully explain the dichotomy between the vertical shift in the production technology frontier and the input driven moment along the frontier.

CHAPTER 8 CONCLUSIONS, IMPLICATIONS, AND LIMITATIONS

This study started from the hypothesis that enabling conditions, such as industrial restructuring and rationalizations that enhanced R&D expenditures coupled with tax incentives resulted in technical efficiency improvements and technological progress in the Canadian sawmilling industry. The hypothesis was tested through the estimated magnitudes of and trends in total factor productivity, capital formation and intensity, scale effects, economies of scale, returns to scale, input substitution elasticities, and price elasticities of derived demand for inputs, using the nonparametric and parametric methods.

Conclusions are drawn in Section 8.1. In Subsection 8.1.1, results of the nonparametric method are used to draw related conclusions, focusing on addressing the research questions under Themes 1 and 2. Then, in Subsection 8.1.2, results of the parametric method are used to examine the conditions postulated under Theme 3 and to draw conclusions accordingly. In Subsection 8.1.3, the strength and limitations of this study are highlighted. Policy implications of the empirical results and future research directions are discussed in Sections 8.2 and 8.3, respectively.

8.1 CONCLUSIONS

8.1.1 Nonparametric and Regression Results

Levels and Growth Rates of Gross TFP: The first research question under Theme 1 deals with the inquiry into the levels and growth rates of gross TFP. Results from the multilateral index model showed that TFP followed upward trends throughout the forty-year study period (1961-2000). The forty-year average annual growth rate was 2.0%. However, annual growth changes revealed significant fluctuations where deep troughs and high peaks were observed.

What should be of concern to the industry is that its TFP performance was better in the earlier periods (1960s and 1980s) than in the later years of the 1990s, when it was sluggish. For example, TFP declined substantially from 3.0% during the period of 1981-1990 to a marginal average annual growth of 0.62% during the period of 1991-2000.

TFP is a closely watched parameter of industrial performance and economic growth. Economists attribute the declining trends in the Canadian industrial productivity since the early 1970s to several factors, which include the following: rising energy and labor prices; insufficient R&D expenditures; declining supply of economically accessible and commercially valuable timber; environmental quality regulatory restrictions; and international trade disputes, such as the U.S. – Canada softwood lumber trade dispute. Thus, also effects of these and similar factors need to be taken into account to conduct a detailed study on TFP.

Sources of TFP Growth: The second question under Theme 1 poses challenges in identifying the main sources of TFP growth. To address that question, results of two regression models are summarized as follows:

Output Effect: Regression of TFP on the aggregate output revealed that the later (i.e., the explanatory variable) had a marginal effect of 0.4429 on TFP. This meant that output accounted for more than 44% of TFP growth. Thus, it can be inferred that strategies focused on expanding production would have improved efficiency, leading to economies of scale.

Output and Time Dependent Technological Progress: The log-linear regression model revealed that elasticity of TFP with respect to output was 0.289. That is, a 1% increase in output would have led to approximately 0.3% growth, *ceteris paribus*. Furthermore, the same model showed that the elasticity of TFP with respect to technological progress over time was 0.62%. This suggests that inventions and innovations through R&D might have played important roles in improving TFP performance of the industry. Thus, the results show that output growth and technological progress jointly contributed to TFP growth.

The parametric results reported in Table 6.1 validate this conclusion. The results of the coefficients on the time trend variable in the four models of the translog form total cost function: the unrestricted, the homothetic, the homogeneous, and the unitary elasticity revealed that the industry recorded average annual growth of TFP within the range of 2% and 3% over the forty-year study period.

The average annual TFP growth obtained with the implementation of the multilateral index model is equal to the growth obtained by estimating the unrestricted translog cost function. Both methods estimated a 2% growth rate of TFP. This is an encouraging outcome that indicates credibility of the data, robustness of the empirical results, and the scientific merit of the joint implementation of the two methods.

Effects of Changes in Taxation Policy Instruments: The business community and policy makers argue that tax incentives are often required to spur capital formation and thereby to enhance productivity and competitiveness. To address the research question under Theme 2, a simulated analysis of the effects of increasing capital cost allowance (CCA) and the investment tax credit (ITC) and of reducing corporate income tax (CIT) was conducted. The results showed that these tax incentives could indeed stimulate capital formation (i.e., net investments in various capital assets and R&D), leading to TFP growth.

8.1.2 Parametric Method

The key outcome of the parametric analysis was that a dual-long-run, nonhomothetic, translog form cost function described the Canadian sawmilling industry's production technology. Thus, the parametric results of that cost function were used to examine the conditions postulated under Theme 3 and to draw conclusions as follows:

Elasticity of the Total Cost: Reflecting the modest gains of economies of scale and returns to scale, the elasticity of the total cost of production with respect to output was less than unity. For example, the average annual elasticity over the study period was 0.249. This value meant that cost increased proportionately less than the proportionate increase in output, such that a 1% rise in output would have resulted in only 0.25% increase in total cost, *ceteris paribus.*

Economies of Scale: Economies of scale are attained within the declining range of the long-run average cost curve. One minus elasticity of total cost provided estimates of economies of scale. An average annual result of 0.751

suggested that the industry had gained modest economies of scale over the forty-year study period.

Returns to Scale: Estimated as a reciprocal of the elasticity of total cost with respect to output, the industry recorded significant increasing returns to scale. Consistent with previous studies, the average annual RTS over the study period was 4.02.

Determinants and Rate of TFP Growth: TFP growth was decomposed into two main determinants: scale effects and cost diminution rate. The sum of the effects of these two technological attributes revealed that the average annual rate of TFP growth was 5.7% over the study period. Thus, combined effect of the mutually reinforcing forces of production scale and cost diminution resulted in measurable TFP growth.

The Dual Measure of the Primal TFP: The change in total cost with respect to time, which is the diminution rate of production cost, is referred to as the dual measure of the primal TFP growth under given input prices and output. A negative value of this measure is an indicator of technological progress. Over the study period, –2.3% average annual value of this measure implied modest contribution of technological progress to TFP growth.

Price Elasticities of Derived Demand for Inputs: While they were statistically significant, both the *own*- and *cross*-price elasticities showed that input demands were price inelastic. This outcome indicated that each input was treated as a "basic" good; and that input price "rigidity" prevailed in the industry over the study period. However, there were opportunities for substituting one input for another to a limited extent. With the exception of capital/energy and energy/capital, which were complements, the pairs of labor/capital, labor/energy, capital/labor, capital/material, energy/labor, and material/capital were substitutes.

Effects of Technological Change-Bias: Over the study period, the Canadian sawmilling industry's production technology was characterized as capital-using, labor- and raw material-saving, and Hicks neutral for energy. This means that there was increasing demand for capital, holding prices of other inputs and output constant. In contrast, management might have minimized demands for labor and raw material as their respective prices increased, *ceteris paribus*. Hicks-neutrality for energy implied that technological change did not affect demand for it.

Input Substitution Elasticities: The input pairs of labor/capital, labor/energy, capital/ material, and energy/ material were substitutes to each other. On the other hand, the pairs of labor/ material and capital/energy were complements. Only the labor/energy substitution elasticity was positive and greater than unity, suggesting that it was easy for the industry to substitute labor for energy.

With the exception of the significant substitutability between labor and energy as well as significant complementarity between capital and energy, all other elasticities were less than unity, implying that it was not that easy for the industry to substitute one input for another.

Three key conclusions are worth reiterating. Firstly, the nonparametric and parametric results showed that technical efficiency improvements and technological progress contributed to the growth of the industry's productivity.

Secondly, it was observed that the industry had gained economies of scale over the study period. Thirdly, it was verified that tax incentives do indeed spur capital formation and consequently enhance TFP.

However, the multilateral index model revealed annual irregularities in TFP over the study period. That is, the Canadian sawmilling industry's annual TFP performance fluctuated rapidly and tended to decline in the later years (i.e., the 1990s) of the forty-year study period.

It is difficult to pin point specific causes of the instability and the tendency to decline, because several factors influence TFP growth. In fact, effects of most of the presumed factors, such as international trade disputes, the globalization of markets, taxation, industrial policy measures, stumpage fee charges, and restrictive environmental regulations, are beyond the control of the industry and the scope of this study.

But, it is recommended that the industry look into the factors over which it has some control and makes necessary adjustments. For example, the following and similar actions will lead to enhanced TFP and thereby an improved competitiveness: increasing investments in R&D; improving quality of human capital through skill upgrading on site and formal training; diversifying output mix; ensuring harmonious relationship between management and labor unions; improving plant level efficiency; and reviewing overall efficiency of the management system.

8.1.3 Some Features of Strength

This study's strength and its contributions to the body of knowledge are summarized here. Several features make it different from any of the previous studies:

Structure of Data: To conduct credible analysis, the statistical adequacy of the data sets, assessed in terms of parsimony, sample size, consistency, and predictive power, is imperative. As detailed in sections 1.3 and 6.4, this aspect is one of the features that established credibility of this study. Compared to the previous studies (Section 6.4) that did not cover more than 20 years, this study has covered 40 years. Thus, historical trends in the data and dynamics of multiple technological attributes were analyzed for a much longer period than was done previously.

Rental Price of Capital: Unlike the previous studies that used various implicit derivation techniques, the perpetual inventory method, which accounts for opportunity cost of a given capital asset, was used in this study. For each of the three assets of capital, the rental price of using a given asset was calculated with the application of the perpetual inventory method (Section 4.2). This rental price reflects the effects of corporate income tax rates, investment tax credits, and property taxes on the true cost of capital investments. It includes the interest cost of the funds in physical assets, economic depreciation, and capital gains or losses due to changing asset prices.

Completeness of Database: A complete database structure that details the multi-output and multi-input nature of the industry was used. Many of the previous studies did not specify the industry's production technology as it was done in this study.

Joint Implementation of Two Major Empirical Methods: This is the main feature that establishes uniqueness of this study. As argued in Chapter 2, there is a need for joint implementation of the nonparametric and parametric methods.

The key scientific merit of the joint implementation is that it enables the researcher to explain the dichotomy between the vertical shift in the production frontier, which is analyzed with the application of the nonparametric method, and the input driven moment along the frontier, which is analyzed with the application of the parametric method.

The following important features make the nonparametric method particularly attractive and credible: it displays input, output, and productivity measures in index form by data point; reveals data anomalies that prompt the researcher to take remedial measures; allows multiregional and international comparisons; enables measurement of productivity levels and growth rates; is easily understood by nonspecialists, such as policy makers and business executives; avoids the usual problems of model specification and estimation associated with parametric models; and explains the degree of vertical shift in the production frontier. In addition, results of this method serve as benchmarks for parametric empirical work due to their simplicity and transparency.

The main drawback of the nonparametric method is that it does not provide parametric measures, such as price elasticities of derived demand for inputs, elasticity of production cost with respect to output, and economies of scale that characterize a given production technology. This can only be achieved by using an econometric method. Thus, the joint implementation of the two methods has strengthened this empirical work.

Factor Cost Shares in Total Cost and Productivity Performance: Factor cost shares provide useful information on resource allocation by revealing the inputs that account the greatest proportion of the total cost of production. With this information, decision makers can target the inputs whose costs need to be minimized so that productivity is improved. The nonparametric method involved calculation of factor shares in total cost that served as weights of the aggregate input quantity and output shares in total revenue that served as weights of the aggregate output in calculating TFP (Section 5.1).

Ten-year interval average annual growth rates revealed that in the 1960s capital, labor, energy, and sawlogs accounted for 9%, 46%, 2%, and 43% of the total cost of production. In the 1990s, however, each factor accounted for 8%, 20%, 2%, and 69%. The shares of capital and energy remained almost constant, while that of labor declined, suggesting declining demand for labor input. The substantial increases in the share of sawlogs implied rising demand for these inputs over the study period, signaling growth in production operations over the years.

Consequently, sawlogs accounted for the least partial factor productivity. This result indicated that sawlogs contributed to the rapidly fluctuating trends in gross TFP. Hence, targeting sawlogs for cost minimization would have been advisable for the industry.

Completeness of the Parametric Measures: The extensive nature of the empirical results adds to the strength and scope of this study. It has used more parametric measures than the previous studies discussed earlier to characterize the Canadian sawmilling industry's production technology.

Taxation Policy Instruments: Taxation policy affects the way in which scarce economic resources are allocated. In this study, the nonparametric method was used to analyze effects of investment tax incentives that involved increasing the capital cost allowance and the income tax credit as well as reducing the corporate income tax on capital formation and TFP growth. It was observed that the tax incentives indeed stimulated capital formation that led to TFP growth.

In short, this study characterizes the Canadian sawmilling industry's production technology more fully than was done previously. The theoretical dichotomy of the vertical shift in the production frontier due to technological progress, inferred through the growth rates of TFP, and the input driven movements along the frontier due to technical efficiency improvements, gauged with several parametric measures, was fully explored with the joint implementation of the two empirical methods. In addition, the effects of investment tax incentives on capital formation and TFP growth were explained.

8.2 INDUSTRIAL POLICY IMPLICATIONS

A. Some Perspectives on Canada's Industrial Forest Policy

Because markets alone cannot achieve required technical efficiency improvements and technological progress, industrial forest policy is necessary. That is, notwithstanding the debate about the degree of a government's intervention to correct market failure and to participate in the workings of the economy, the market mechanism left on its own leads to sub-optimal outcomes in many cases. Thus, a range of industrial policy instruments is needed to foster productivity and thereby economic growth.

At the federal level, Canada's industrial policy instruments aim at improving macroeconomic performance; maintaining competitive positions of industries in the global marketplace; assisting the provincial and territorial governments in managing natural resources in a sustainable manner; diversifying and developing community-based economies; and enhancing R&D investments.

Specific policy instruments that focus on forest resource-based industries are crucial in Canada, not only because Canadians demand for sustainable supply of the multiple benefits from their forest resources, but also because forest products' export earnings account a larger share of trade balance, varying by province. For example, in 2005, the Canadian Forest Service reported that the total value of Canadian forest-products' export earnings was $41.9 billion, which was regionally distributed as British Columbia, $13.7 billion (33%); Quebec, $11.6 billion (28%); Ontario, $8.4 billion (20%); and other provinces, $8.2 billion (20%).

The Canadian forestland tenure system also plays important role in sustainable forest ecosystem management. The 10 provinces and three territories have jurisdictional authority over 77% of Canada's forest resources (Canadian Forest Service 2006a). They develop and enforce policy instruments; allocate timber-harvesting licences; set and collect stumpage fees; and collect data. The federal government is steward of 16% of the national forest resources, while 7% is owned privately. The federal government is responsible for matters related to the national economy (e.g., fiscal and monetary policies), international trade and investments, federal lands and parks, and forest resource development issues that deal with Aboriginal peoples.

Moreover, the rising trends in globalization and Canada's commitment to the rules of several international trade organizations (e.g., GATT and WTO) and to the Kyoto Protocol on climate change have implications on the economic performance and competitiveness of forest products industries.

Thus, the multidimensionality of the federal government's industrial forest policy has implications for technical efficiency improvements and technological progress in the sawmilling industry. This study implemented two major empirical methods jointly to examine the effects of an array of issues on the productivity performance of the Canadian sawmilling industry. Several nonparametric and parametric measures were used to analyze dynamics of multiple technological attributes over a forty-year period.

B. Implications of the Key Empirical Findings

Because of the extensive nature of the nonparametric and parametric findings, policy implications of the key ones are summarized here.

Total Factor Productivity: Total factor productivity (TFP) growth is considered as one of the engines of economic growth. Its importance is manifested through the facts that it has become a workhorse of empirical economic growth analysis and that it is a closely watched government statistic.

TFP is a consequence of the dynamics of several forces, such as technological progress attained mainly through enhanced investments in R&D, the quality of human and physical capital, institutional arrangements, and efficiency of the management system. It is the best available yardstick to measure and analyze performance of a given economic entity, such as a firm and an industry.

For the purpose of this study, TFP growth is considered as an indicator of output growth realized through the combined effects of scale of production and technological progress, revealed through the rate of cost diminution. The two mutually reinforcing effects cause vertical shift in the frontier of the production technology.

Annual growth results revealed that the Canadian sawmilling industry's TFP fluctuated rapidly over the study period. In addition, it was observed that the industry's TFP performance was better in the earlier periods (1960s and 1980s) than in the later years of the 1990s, when it was sluggish. Thus, it is recommended that the industry take immediate policy measures to improve its TFP performance. The measures can involve overall restructuring and rationalization as well as enhanced investments in R&D and in human capital quality improvement through formal and informal (on site) training.

Input Substitution Elasticities: One of the implications of the cost minimization assumption in studies such as this is that a rise in one input's cost increases total cost, calling for substituting one input, whose price is lower for another, whose price is higher. For this to be realized, however, the degree of substitutability, i.e., the elasticity of input substitution, must be greater than unity.

In this study, less than unity elasticities of substitution between pairs of most of the inputs revealed that the industry experienced limited input substitution opportunities over the study period. Hence, it can be inferred that the lack of flexibility in input substitution might have contributed to the fluctuation of TFP over the study period.

However, the nature of substitutability by itself has some merits. For example, because sawlogs accounted for nearly 70% of the total cost of production, the limited degree of substitutability between capital and sawlogs (the sole raw material) suggested that introducing technology (e.g., modernizing equipment and machinery) that would have enhanced efficiency in harvesting timber and in processing sawlogs would have been an important policy action to minimize cost.

According to the AES results, the input pairs of labor/material and capital/energy were complements. Complementarity has important implications on cost of production. For example, if rental price of capital rose, the price of energy also would rise. This would lead to significant rise in total cost. Thus, targeting the pairs of inputs for cost minimization would be advisable for the Canadian sawmilling industry.

Own- and Cross-Price Elasticities of Derived Demand for Inputs: Only capital and energy were found to be complements in production, while the other inputs were substitutes. The highly inelastic nature of the price elasticities indicated that each input was treated as a "basic" good; and, hence, there was input price "rigidity". This condition is believed to be one of the sources of inefficiency along the production line, because cross-price effects, substitution effects, and output effects are mutually reinforcing factors that influence the demand for an input and thereby productivity.

Impacts of Biased Technological Change: The production technology of the Canadian sawmilling industry was characterized as capital-using, energy-saving, and Hicks-neutral for labor and material. That is, technological change resulted in rising demand for capital; declining demand for energy; and no effect on the individual demand functions for labor and material, *ceteris paribus*.

Biased technological change has important economic implications that call for a continual research on the dynamics of factor supply and demand. For example, the capital-using result suggests need for investments in machinery, equipment, and computer hardware and software in order to improve efficiency. On the other hand, the Hicks-neutrality on labor and material implies that technological change in the Canadian sawmilling industry might have led to the use of labor and material proportionately to produce an optimal output, Q^*, leaving the marginal rate of technical substitution of martial for labor or vise versa as well as the price ratio of the two inputs fixed. That is, the isoquant moved inward (toward the origin) along the expansion path in the production process of Q^* at a least-cost combination of the two inputs. Moreover, the declining demand for energy might be attributed to the rising trends in its price.

8.3 LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

8.3.1 Limitations

Strength and value of this study were highlighted in Subsection 8.1.3. However, like any other empirical work, this study has limitations.

Industry Level Data: In this study, like in all previous studies, using industry level data was based on a strong assumption that perfectly competitive firms in the Canadian sawmilling industry were homogeneous in organizational behavior. That is, all decision making units (DMUs), reacted equally and similarly to shocks from market and non-market forces. This is very unlikely, because each DMU has its own unique goals, objectives, resource constraints, and organizational structure.

However, using national level, aggregated, industrial data was the only way to obtain data on capital in order to specify the long-run production function and subsequently the dual long-run cost function that provided full information on the industry's production technology. In fact, this is the main reason why all previous studies used industry level data. In Canada, secondary capital data are not available at the firm or provincial levels.

Supply Side Focus: This study examined only the dynamics of technological attributes of the industry. Thus, focus on the supply side only does not explain fully the competitive position of the industry in the marketplace.

The Role of Time Trend Variable: Using time trend variable as a proxy measure of technological progress is not reliable, because it is used under a strong assumption that technological progress is smooth and steady. If the objective is to obtain an exact measure *of* technological progress, this problem is quite serious. But, if the objective is to test for the existence of technological change and statistical significance of its impact on production cost, this approach is valid. Hence, like all previous studies (Section 3.1), this study used time as an indicator of presence of technological progress over the forty-year study period.

8.3.2 Future Research Directions

To rectify the above identified limitations, the following long-term research projects are warranted:

Firm Level Studies: Although by far more effective than economy wide (macroeconomic) studies, industrial studies are less effective than firm specific studies. That is, decision-making unit (DMU) level cost and/or production function models are statistically more effective in generating credible parametric results than those specified at industry level. This is because the models are not affected by the usual data aggregation problems associated with industry and macroeconomic data. Particularly, parameters such as economies of scale and returns to scale are more meaningful at the firm level than at an industry level. In addition, DMU level studies conducted at provincial levels will have highly relevant industrial policy implications. But, it should be realized that there would be challenges in acquiring correct annual flow and stock of capital data.

North American Inter-regional Comparative Studies: There are at least three regions between Canada and the United Sates where there are distinctively different links of trade. The rates and types of the flow of goods and services between the Canadian Maritime Provinces and the state of Maine are different from those between the central Canada provinces of Ontario and Quebec, which are closely linked to the Lake States. The same situation applies between the Prairie Provinces and British Columbia, which have close trade ties with the western states of the United States. In short, there are opportunities for conducting interregional comparative analyses of productivity performance of production technologies of the Canadian and American sawmilling industries. The same projects can be initiated for the pulp and paper industries and other forest products' industries.

To sum up, despite the limitations, several features have established the strength and uniqueness of this study. Unlike other previous studies, the statistical adequacy of the empirical work has been validated. The joint implementation of the nonparametric method and the parametric method made it possible to use dynamics of multiple technological attributes to fully explore the dichotomy between the vertical shift in the production technology frontier, realized through technological progress, and the input driven movements along the frontier, realized through technical efficiency improvements. Important policy implications of the empirical findings were also highlighted.

APPENDICES

Appendix A. Primary variables and their sources, and derived variables

Table A.1. Industrial output data

VARIABLES	SOURCES
Total lumber output	The Canadian Forest Service (2006a). *Selected Forestry Statistics Canada*, Table I-4, complete time series from http://www.nrcan.gc.ca/selfor/1_com_prod_ship/new/I-4_tot_e.htm (accessed June 2006).
Quantity and value of lumber shipments for deriving implicit price series	1) The Canadian Forest Service (2001). *Selected Forestry Statistics Canada Special Edition – Historical Series,* Table I-6 for the 1970-96 period 2) Statistics Canada Catalogue No. 35-204 and 35-250 for 1961-69 and 1997, while the three data points (1998-00) were estimated based on the historical series.
Value added in production of shakes and shingles	1) The Canadian Forest Service, Selected Forestry Statistics Canada, *Information Reports*: E-X-34 (1984) Table IV-4 for 1970-82 and E-X-48 (1995) Table III-17 for 1983-1993; and for 1994-00 from http://www2.nrcan.gc.ca/cfs-scf/selfor/default.html, (accessed June 2006) 2) Statistics Canada Catalogue No. 35-204, 35-250, and 31-203 for 1961-69
Industrial product price index (IPPI) (1992 = 100) for shakes and shingles for deriving implicit quantity series	The Canadian Forest Service (2001). *Selected Forestry Statistics Canada Special Edition – Historical Series, Table V-1* complete series for 1961-99; and Statistics Canada Catalogue No. 62-011 for year 2000

Aggregate quantities and prices of wood residues sold to pulp mills	1) Quantities and prices: Manning, G.H. 1972. The utilization of wood residue in Canada. Info. Rep. E-X-13, Forest Economics and Research Institute, Environment Canada, Forestry Service, for 1961-68 2) Quantities and prices: (a) The Canadian Forest Service (2001). *Selected Forestry Statistics Canada Special Edition – Historical Series, Table I-3* for the 1970-99 and (b) for 1969 Statistics Canada Cat. No. 25-001; 35-204, and 35-003, while the single data point for 2000 was estimated, based on the historical data. 3) IPPI (1992 = 100) for wood industries from The Canadian Forest Service (2001), *Selected Forestry Statistics Canada Special Edition – Historical Series, Table V-1* for 1961-99 and Statistics Canada Catalogue No. 62-011 for year 2000

Table A. 2. Industrial input data

VARIABLES	SOURCES
Capital: (a) current and real dollar expenditures and (b) price indices and rates of depreciation for each of the three components	Special request from Capital Stock Division, Statistics Canada (details in Section 4.2).
Miscellaneous rates for computing capital rental prices: (i) investment tax credit, (ii) corporate income tax, (iii) capital cost allowance, and (iv) Scotia McLeod bond yield	Obtained from the database of Ghebremichael and Nanang (2004)
Labor: Two sets: (a) total number of employees and salaries and wages in production activities and (b) total number of employees and salaries and wages in management and admin. Activities	Selected Forestry Statistics Canada, Table III-11A. *Principal Statistics* for 1961-97 in http://www2.nrcan.gc.ca/cfs-scf/selfor/default.html, (accessed June 2006) Three data points (1998-00) were estimated based on the historical series.
Energy: (a) total cost of fuels and electricity and (b) industrial energy consumption price indices for	(a) Cost of fuels and electricity from Selected Forestry Statistics Canada, Table III-11A. *Principal Statistics* from 1961-97 in http://www2.nrcan.gc.ca/cfs-scf/selfor/default.html, (accessed June 2006)

deriving implicit quantity series	Three data points (1998-00) were estimated based on the historical series (b) Department of Finance Canada, *Economic Reference Tables* (old title) and *Fiscal Reference Tables* (new title)
Sawlogs: (i) quantities and (ii) prices	(i) Complete annual series from *Selected Forestry Statistics Canada*, Table I-1 in http://www2.nrcan.gc.ca/cfs-scf/selfor/default.html, (accessed June 2006) (ii) Implicit price series were derived from quantities and values of shipments from Statistics Canada Catalogue No.25-201

Appendix B. Time series of Selected Empirical Results: Summary

Results summarized in Tables B.1, B.2, and B.3 (Appendix B) and in Tables C.1 and C.2 (Appendix C) were obtained *without* changes in CCA, ITC, and CIT. Summarized in Tables D.1, D.2, D.3, and D.4 (Appendix D) are results *with* the changes.

Table B.1. Factor shares in total cost *without* the changes in taxation for the Canadian sawmilling industry: 1961-2000

Year	Capital	Labor	Energy	Material
1961	8.4	57.9	1.3	32.5
1962	8.4	52.5	1.5	37.6
1963	7.5	52.6	1.4	38.5
1964	7.7	47.9	1.6	42.8
1965	7.8	46.3	1.5	44.4
1966	8.6	44.3	1.6	45.5
1967	9.1	42.1	1.7	47.1
1968	9.3	40.8	1.6	48.3
1969	9.2	37.5	1.5	51.8
1970	10.5	40.6	1.4	47.5
1971	9.6	42.3	1.5	46.6
1972	8.9	44.1	1.6	45.4
1973	7.0	41.2	1.5	50.4
1974	7.3	42.7	2.0	48.3
1975	8.8	41.8	2.0	47.5
1976	7.1	39.0	2.0	52.0
1977	6.1	39.2	2.1	52.7
1978	6.1	39.9	2.1	51.9
1979	6.6	36.7	2.0	54.7
1980	7.9	36.6	2.2	53.3
1981	10.1	37.9	2.8	49.2
1982	10.7	35.1	3.2	51.1
1983	8.6	33.8	3.2	54.3
1984	9.1	33.1	3.3	54.5
1985	9.1	33.4	3.3	54.3
1986	9.7	30.7	2.9	56.6
1987	9.3	32.1	2.5	56.2
1988	9.3	27.5	2.4	60.8
1989	9.7	27.1	2.4	60.8
1990	11.6	27.6	2.6	58.1
1991	11.3	24.5	2.5	61.8
1992	9.8	23.5	2.5	64.2
1993	8.2	22.1	2.3	67.5
1994	8.1	21.3	2.2	68.5
1995	7.6	19.3	2.0	71.1
1996	7.5	19.9	2.1	70.5
1997	7.8	20.0	2.1	70.1
1998	8.4	20.5	2.2	68.8
1999	7.6	18.3	2.1	71.9
2000	8.1	18.0	2.1	71.8

Table B.2. Trends in input quantities *without* the changes in taxation for the Canadian sawmilling industry: 1961-2000

Year	Capital	Labor	Energy	Material
1961	1.00	1.00	1.00	1.00
1962	1.00	1.01	1.14	1.06
1963	1.01	1.03	1.22	1.11
1964	1.02	1.04	1.24	1.12
1965	1.04	1.04	1.28	1.13
1966	1.06	1.03	1.33	1.14
1967	1.06	1.01	1.30	1.14
1968	1.08	1.02	1.31	1.17
1969	1.14	1.04	1.34	1.22
1970	1.19	1.02	1.31	1.24
1971	1.23	1.05	1.43	1.26
1972	1.28	1.11	1.57	1.29
1973	1.35	1.16	1.56	1.41
1974	1.40	1.12	1.60	1.32
1975	1.43	1.03	1.81	1.23
1976	1.45	1.10	1.94	1.41
1977	1.46	1.14	1.91	1.45
1978	1.48	1.20	1.90	1.51
1979	1.52	1.21	2.16	1.53
1980	1.55	1.19	2.22	1.50
1981	1.57	1.16	2.22	1.40
1982	1.55	1.07	2.17	1.35
1983	1.53	1.11	2.17	1.51
1984	1.52	1.12	2.15	1.55
1985	1.50	1.13	2.30	1.56
1986	1.51	1.11	2.26	1.60
1987	1.55	1.15	2.36	1.70
1988	1.61	1.15	2.20	1.68
1989	1.63	1.12	2.20	1.68
1990	1.63	1.07	2.23	1.56
1991	1.60	1.02	2.12	1.57
1992	1.58	1.06	2.25	1.64
1993	1.59	1.10	2.23	1.68
1994	1.64	1.16	2.34	1.71
1995	1.69	1.16	2.37	1.75
1996	1.71	1.17	2.43	1.73
1997	1.75	1.19	2.27	1.75
1998	1.76	1.19	2.04	1.70
1999	1.75	1.19	2.09	1.84
2000	1.76	1.19	2.04	1.84

Table B.3. Output shares in total revenue *without* the changes in taxation for the Canadian sawmilling industry: 1961-2000

Year	Outputs and their respective shares (%)		
	Lumber	Shakes & Shingles	Wood Residues
1961	89.18	1.34	9.47
1962	90.74	1.37	7.89
1963	89.94	1.81	8.26
1964	88.79	1.30	9.92
1965	85.82	1.14	13.04
1966	86.93	1.03	12.04
1967	82.22	1.34	16.44
1968	82.99	1.70	15.31
1969	80.27	1.30	18.43
1970	74.38	1.08	24.53
1971	88.23	1.66	10.11
1972	90.08	1.61	8.31
1973	91.20	1.20	7.59
1974	85.98	1.02	13.00
1975	82.22	1.80	15.98
1976	83.14	1.62	15.24
1977	86.95	1.46	11.59
1978	89.09	1.47	9.44
1979	89.51	1.06	9.43
1980	84.97	1.26	13.77
1981	80.97	1.18	17.85
1982	80.84	0.95	18.21
1983	86.06	0.79	13.15
1984	84.46	0.99	14.55
1985	82.89	1.11	16.00
1986	83.39	1.15	15.47
1987	81.33	0.98	17.69
1988	80.21	0.94	18.84
1989	77.05	0.92	22.03
1990	73.68	1.10	25.22
1991	74.74	0.96	24.30
1992	79.88	1.03	19.08
1993	84.26	0.74	15.00
1994	82.23	0.56	17.21
1995	69.81	0.55	29.63
1996	82.50	0.66	16.84
1997	84.71	0.74	14.55
1998	83.38	0.66	15.96
1999	84.82	0.43	14.74
2000	80.99	0.77	18.23

Appendix C. Partial and Total Factor Productivities and Aggregate Output and Input Quantities

Table C.1. Partial factor productivity indices *without* the changes in taxation for the Canadian sawmilling industry: 1961-2000

Year	Capital	Labor	Energy	Material
1961	1.00	1.00	1.00	1.00
1962	1.08	1.08	0.95	1.03
1963	1.20	1.17	0.99	1.09
1964	1.24	1.22	1.02	1.13
1965	1.28	1.28	1.05	1.18
1966	1.28	1.32	1.01	1.19
1967	1.26	1.33	1.04	1.18
1968	1.38	1.46	1.13	1.27
1969	1.37	1.51	1.16	1.27
1970	1.33	1.55	1.21	1.28
1971	1.47	1.72	1.26	1.43
1972	1.56	1.80	1.27	1.55
1973	1.64	1.92	1.43	1.58
1974	1.44	1.81	1.26	1.53
1975	1.19	1.65	0.94	1.39
1976	1.60	2.10	1.19	1.64
1977	1.75	2.24	1.33	1.75
1978	1.85	2.29	1.44	1.82
1979	1.88	2.36	1.33	1.87
1980	1.80	2.34	1.26	1.86
1981	1.61	2.19	1.14	1.81
1982	1.50	2.18	1.08	1.73
1983	1.94	2.66	1.36	1.97
1984	1.98	2.68	1.40	1.94
1985	2.23	2.97	1.46	2.15
1986	2.24	3.05	1.50	2.12
1987	2.49	3.34	1.63	2.28
1988	2.36	3.31	1.73	2.26
1989	2.30	3.33	1.70	2.23
1990	2.16	3.28	1.58	2.26
1991	2.11	3.33	1.60	2.16
1992	2.28	3.40	1.60	2.20
1993	2.40	3.47	1.71	2.27
1994	2.46	3.50	1.73	2.36
1995	2.47	3.60	1.76	2.38
1996	2.41	3.52	1.70	2.39
1997	2.41	3.55	1.85	2.40
1998	2.36	3.50	2.03	2.44
1999	2.69	3.96	2.25	2.56
2000	2.77	4.13	2.40	2.65

Table C.2. Trends in aggregate input and output quantities and TFP *without* the changes in taxation for the Canadian sawmilling industry: 1961-2000

Year	Output	Input	TFP
1961	1.00	1.00	1.00
1962	1.08	1.05	1.03
1963	1.21	1.12	1.08
1964	1.27	1.14	1.12
1965	1.34	1.15	1.16
1966	1.35	1.15	1.18
1967	1.34	1.12	1.20
1968	1.49	1.17	1.27
1969	1.56	1.25	1.25
1970	1.59	1.27	1.25
1971	1.81	1.32	1.36
1972	1.99	1.43	1.39
1973	2.22	1.63	1.36
1974	2.02	1.49	1.35
1975	1.70	1.31	1.30
1976	2.31	1.60	1.44
1977	2.54	1.70	1.50
1978	2.74	1.83	1.49
1979	2.86	1.89	1.51
1980	2.79	1.84	1.52
1981	2.53	1.69	1.50
1982	2.33	1.53	1.53
1983	2.97	1.76	1.68
1984	3.01	1.82	1.65
1985	3.36	1.85	1.81
1986	3.39	1.88	1.80
1987	3.86	2.07	1.86
1988	3.80	2.07	1.84
1989	3.74	2.04	1.84
1990	3.52	1.82	1.94
1991	3.39	1.77	1.91
1992	3.60	1.91	1.88
1993	3.81	2.02	1.89
1994	4.04	2.15	1.88
1995	4.17	2.23	1.87
1996	4.14	2.22	1.86
1997	4.20	2.26	1.86
1998	4.15	2.18	1.91
1999	4.70	2.40	1.96
2000	4.89	2.41	2.03

Appendix D. Selected Empirical Results *with* the Changes in Taxation

Table D.1. Share of each input in total cost *with* the changes in taxation for the Canadian sawmilling industry: 1961-2000

Year	Capital	Labor	Energy	Material
1961	11.7	55.8	1.2	31.3
1962	11.6	50.6	1.4	36.3
1963	10.5	50.9	1.4	37.2
1964	10.8	46.3	1.5	41.3
1965	11.1	44.6	1.5	42.8
1966	12.1	42.6	1.6	43.8
1967	12.7	40.5	1.6	45.2
1968	12.3	39.4	1.6	46.6
1969	12.3	36.2	1.4	50.0
1970	13.9	39.0	1.4	45.7
1971	13.7	40.4	1.5	44.4
1972	13.0	42.2	1.5	43.4
1973	11.0	39.4	1.4	48.2
1974	11.7	40.7	1.6	46.0
1975	14.7	39.1	1.8	44.4
1976	12.1	36.9	1.8	49.2
1977	11.0	37.1	2.0	49.9
1978	10.6	38.0	2.0	49.4
1979	10.2	35.3	1.9	52.6
1980	11.5	35.2	2.1	51.2
1981	14.1	36.2	2.6	47.0
1982	15.2	33.3	3.1	48.5
1983	12.5	32.4	3.1	52.0
1984	12.7	31.8	3.1	52.4
1985	12.6	32.1	3.1	52.2
1986	13.1	29.6	2.8	54.5
1987	12.4	30.9	2.4	54.3
1988	13.2	26.3	2.3	58.2
1989	13.6	25.9	2.3	58.2
1990	15.8	26.3	2.5	55.4
1991	15.1	23.4	2.4	59.1
1992	13.2	22.6	2.4	61.8
1993	11.4	21.4	2.2	65.1
1994	11.2	20.5	2.1	66.1
1995	10.8	18.6	1.9	68.7
1996	10.7	19.2	2.0	68.1
1997	11.0	19.3	2.1	67.6
1998	11.7	19.8	2.2	66.4
1999	10.6	17.7	2.1	69.6
2000	11.0	17.4	2.0	69.6

Table D.2. Shares of capital in total cost, *without* and *with* changes in taxation for the Canadian sawmilling industry: 1961-2000

Year	Shares (%)		
	Without (Sck1)	*With* (Sck2)	Change = (Sck2-Sk1)
1961	8.4	11.7	3.3
1962	8.4	11.6	3.2
1963	7.5	10.5	3.0
1964	7.7	10.8	3.2
1965	7.8	11.1	3.3
1966	8.6	12.1	3.5
1967	9.1	12.7	3.6
1968	9.3	12.3	3.1
1969	9.2	12.3	3.1
1970	10.5	13.9	3.4
1971	9.6	13.7	4.1
1972	8.9	13.0	4.1
1973	7.0	11.0	4.0
1974	7.3	11.7	4.4
1975	8.8	14.7	5.9
1976	7.1	12.1	5.0
1977	6.1	11.0	4.9
1978	6.1	10.6	4.5
1979	6.6	10.2	3.6
1980	7.9	11.5	3.6
1981	10.1	14.1	4.1
1982	10.6	15.2	4.5
1983	8.6	12.5	3.9
1984	9.1	12.7	3.5
1985	9.1	12.6	3.5
1986	9.7	13.1	3.3
1987	9.3	12.4	3.1
1988	9.3	13.2	3.9
1989	9.6	13.6	4.0
1990	11.6	15.8	4.2
1991	11.3	15.1	3.8
1992	9.8	13.2	3.5
1993	8.2	11.4	3.2
1994	8.0	11.2	3.2
1995	7.6	10.8	3.2
1996	7.5	10.7	3.2
1997	7.8	11.0	3.2
1998	8.4	11.7	3.3
1999	7.6	10.6	3.0
2000	8.1	11.0	2.9

Table D.3. Capital intensity *without* and *with* changes in taxation for the Canadian sawmilling industry: 1961-2000

Year	Without	With	Growth (%)
1961	1801.14	2603.62	44.55
1962	1857.55	2662.85	43.35
1963	1840.51	2647.15	43.83
1964	1857.61	2717.38	46.28
1965	1945.04	2876.68	47.90
1966	2186.75	3197.39	46.22
1967	2349.64	3410.07	45.13
1968	2614.60	3602.41	37.78
1969	2978.81	4138.85	38.94
1970	3540.78	4894.60	38.24
1971	3458.61	5185.78	49.94
1972	3400.45	5201.61	52.97
1973	3282.02	5393.84	64.34
1974	3701.26	6215.85	67.94
1975	4773.00	8536.50	78.85
1976	4506.90	8151.51	80.87
1977	4251.60	8070.12	89.81
1978	4598.97	8429.42	83.29
1979	5994.18	9571.75	59.68
1980	7605.27	11496.72	51.17
1981	9548.51	14035.42	46.99
1982	11371.90	17070.21	50.11
1983	10288.68	15625.12	51.87
1984	11435.83	16501.15	44.29
1985	11708.45	16883.66	44.20
1986	13493.56	18816.34	39.45
1987	15094.84	20945.74	38.76
1988	15422.61	22821.86	47.98
1989	16591.57	24547.00	47.95
1990	20425.74	29189.33	42.90
1991	22649.82	31667.53	39.81
1992	20184.37	28401.46	40.71
1993	18535.52	26798.29	44.58
1994	19487.47	28207.27	44.75
1995	20866.33	30695.27	47.10
1996	20321.47	29924.69	47.26
1997	21092.15	30931.07	46.65
1998	22279.52	32016.95	43.71
1999	22543.67	32332.54	43.42
2000	24229.84	34133.15	40.87

Table D.4. TFP1, TFP2, and rates of their marginal differences for the Canadian sawmilling industry: 1961-2000

Year	TFP1 (*without*)	TFP2 (*with*)	*Marginal difference* (%)= (TFP2-TFP1)x100
1961	1.0000	1.0000	0.0000
1962	1.0330	1.0331	0.0095
1963	1.0788	1.0790	0.0143
1964	1.1163	1.1161	-0.0181
1965	1.1615	1.1603	-0.1204
1966	1.1796	1.1772	-0.2415
1967	1.1956	1.1924	-0.3145
1968	1.2719	1.2676	-0.4335
1969	1.2510	1.2436	-0.7459
1970	1.2532	1.2429	-1.0272
1971	1.3649	1.3518	-1.3087
1972	1.3943	1.3796	-1.4614
1973	1.3630	1.3467	-1.6336
1974	1.3502	1.3277	-2.2487
1975	1.2972	1.2670	-3.0169
1976	1.4449	1.4190	-2.5844
1977	1.4998	1.4744	-2.5351
1978	1.4948	1.4703	-2.4428
1979	1.5132	1.4866	-2.6545
1980	1.5170	1.4873	-2.9750
1981	1.4977	1.4641	-3.3600
1982	1.5273	1.4904	-3.6916
1983	1.6822	1.6499	-3.2340
1984	1.6518	1.6220	-2.9798
1985	1.8140	1.7827	-3.1283
1986	1.7985	1.7673	-3.1160
1987	1.8638	1.8317	-3.2120
1988	1.8394	1.8031	-3.6251
1989	1.8362	1.7980	-3.8106
1990	1.9351	1.8895	-4.5633
1991	1.9139	1.8710	-4.2902
1992	1.8814	1.8445	-3.6886
1993	1.8864	1.8508	-3.5577
1994	1.8830	1.8450	-3.7946
1995	1.8736	1.8341	-3.9511
1996	1.8619	1.8204	-4.1410
1997	1.8616	1.8185	-4.3121
1998	1.9070	1.8605	-4.6445
1999	1.9579	1.9148	-4.3081
2000	2.0274	1.9818	-4.5546

References

REFERENCES

Abt, R.C. 1987. An analysis of regional factor demand in the U.S. industry. For. Sci. 33(1): 164-173.

Aghion, P.; Howitt, P. 1999. Endogenous growth theory. The MIT Press, Cambridge, Massachusetts (3rd print). 694 p.

Allen, R. G. D. 1938. Mathematical analysis for economists. Macmillan, London. 548 p.

Arrow, K.J.; Chenery, H.B.; Minhas, B.S.; Solow, R.M. 1961. Capital-labor substitution and economic efficiency. The Rev. Econ. & Stats. 43(3): 225-250.

Baardsen, S. 2000. An econometric analysis of Norwegian sawmilling 1974-1991 based on mill-level data. *Forest Sci.* 46(4): 537-547.

Banskota, K.; Philips, W.; Williamson, T. 1985. Input substitution and economies of scale in the Alberta sawmilling industry. Can. J. For. Res.15: 1025-1030.

Baldwin, J.R.; Dhaliwal, N. 2000. Labor productivity differences between domestic and foreign-controlled establishments in the Canadian manufacturing sector. 11F0019MPE No. 118. Statistics Canada, Ottawa, ON.

Beattie, B.R.; Taylor, C.R. 1985. The economics of production. John Wiley & Sons, Inc., New York, NY. 258 p.

Barro, R.J. 1990. Government spending in a simple model of endogenous growth. The. J. Pol. Econ. 98(5), Part 2: S103-S125.

Bernd, E.R.; Wood, D.O. 1975. Technology, prices, and the derived demand for energy. The Rev. Econ. & Stats. 57(3): 259-268.

Berndt, E.R.; Watkins, G.C. 1981. Energy prices and productivity trends in the Canadian manufacturing sector, 1957-76: some exploratory results. Canadian Government Publishing Centre, Supply and Services Canada, Ottawa, ON. Cat. No. EC-22-

Berndt, E.R. 1991. The practice of econometrics, classic and contemporary. Addison-Wesley Publishing Company, Reading, Massachusetts. 702 p.

Betts, J.R. 1998. Canada in the 21st century, II. resources and technology: the implications of technological change for human resource policy. Paper Number 7, Industry Canada, Ottawa, ON. 62 p.

Betts, J.R. 1994. Technological change, sectoral shift, and distribution of earnings: a human capital model. Economica, 61(244): 475-492

Bhattacharyya, Anjana; Bhattacharyya, Arunava; Mitra, Krishna. 1997. Decomposition of technological change and factor bias in Indian power sector: an unbalanced panel data approach. Journal of Productivity Analysis, 8: 35-52.96/1981E

Binswanger, H.P. 1974a. A cost function approach to the measurement of elasticities of factor demand and elasticities of substitution. Am. J. Agr. Econ. 56(2): 377-386.

Binswanger, H.P. 1974b. The measurement of technical change biases with many factors of production. Am. Econ. Rev. 64(6): 964-976.

Binswanger, H.P. 1974c. The measurement of technical change biases with many factors of production. Am. Econ. Rev. 64(6): 964-976.

Blackorby, C.; Russell, R. R. 1989. Will the real elasticity of substitution please stand up? A comparison of the Allen/Uzawa and Morishima elasticities. Am. Econ. Rev. 79(4): 882-888.

Bittlingmayer, G. 1988. Property rights, progress, and the aircraft patent agreement. J. Law & Econ., 31(1): 227-248.

Boskin, M.J.; Lau, L.J. 1992. Capital, technology, and economic growth. Pages 17-55 in Rosenberg, Landau, and Mowery, eds. Technology and the wealth of nations. Stanford University Press, Stanford, California. 389 p.

Bosworth, B.; Perry, G. 1994. Productivity and real wages: is there a puzzle. Brookings Papers on Economic Activity, Vol. 1994, No. 1: 317-344.

Buongiorno, J.; Gilless, J. K. 1980. Effects of input costs, economies of scale, and technological change on international pulp and paper prices. Forest Sci. 26(2): 261-275.

Burkett, P. 2006. Total factor productivity: an ecological-economic critique. Organization & Environment, 19(2): 171-190.

Canadian Chamber of Commerce. 2004. 2004 policy resolution, finance and taxation. Ottawa, ON. 8 p.

Canadian Forest Service. 2006a. http://www2.nrcan.gc.ca/cfs-scf/selfor/default.html, (accessed June 2006)

Canadian Forest Service. 2006b. The state of Canada's forests: forest industry competitiveness. The Canadian Forest Service, Natural Resources Canada, Ottawa, ON. 79 p.

Canadian Forest Service. 2005.The state of Canada's forests 2004-2005: the boreal forest, The Canadian Forest Service, Natural Resources Canada, Ottawa, ON. 96 p.

Canadian Forest Service. 2003. National forest 2003-2008 strategy, a sustainable forest: the Canadian Commitment. Natural Resources Canada, Ottawa, ON. 28 p.

Canadian Forest Service. 2001. Selected Forestry Statistics Canada Special Edition – Historical Series. Natural Resources Canada, Ottawa, ON, 376 p.

Canadian Forest Service. 2000. The state of Canada's forests 1999 – 2000: Forests in the new millennium. Natural Resources Canada, Ottawa, ON. 120 p.

Canadian Forest Service (various years). Selected forestry statistics, various issues of *Information Report*. Economics, Industry, and Programs Directorate, Hull, Que.

Canada Revenue Agency. 1994. IT-285R2 Capital cost allowance-general comments. http://www.cra-arc.gc.ca/E/pub/tp/it285r2/it285r2-e.html (accessed Oct. 25, 2006).

Carlaw, K.I.; Lipsey, R.G. 2003. Productivity, technology, and economic growth: what is the relationship? J. Econ. Survey, 17(3): 457-495.

Carter, D. R.; Cubbage, F. W. 1994. Technological efficiency and industry evolution in southern U.S. pulpwood harvesting. Canadian Journal of Forest Research 24(2): 217-224.

Carter, D.R., Cubbage, F.W. 1995. Stochastic frontier estimation and sources of technological efficiency in Southern timber harvesting. Forest Sci. 41(3): 576-593.

Caves, D.W.; Christensen, L.R. 1980. Global properties of flexible forms. The Am. Econ. Rev., 70(3): 422-432.

Caves, D.W.; Christensen, L.R.; Tretheway, M.W. 1981. U.S. trunk air carriers, 1972-1977: a multilateral comparison of total factor productivity. Pages 47-76 in T.G. Cowing and R.E. Stevenson, eds. Productivity measurement in regulated industries. Academic Press, New York, NY. 417 p.

Caves, D.; Christensen, L.R.; Diewert, D.E. 1982a. Multilateral comparisons of output, inputs, and productivity using superlative index numbers. Econ. J. 92:73-86.

Caves, D. Christensen, L.R.; Diewert, W.E. 1982b. Economic theory of index numbers and the measurement of input, output, and productivity. Econometrica 50(6):1393-1413.

Chambers, R.G. 1988. Applied production analysis: a dual approach. Cambridge University Press, New York. 331 p.

Chiang, A.C. 1984. Fundamental methods of mathematical economics (3rd edn.). McGraw-Hill Book Company, New York. 788 p.

Christensen, L.R., Jorgenson, D. W., 1969. The measurement of U.S. real capital input, 1929-1967. Rev. Income Wealth 15(4): 293-320.

Christensen, L.R.; Jorgenson, D.W.; Lau, L.J. 1973. Transcendental logarithmic production frontiers. The Rev. Econ. & Stats. 55(1): 28-45

Christensen, L.R. 1975. Concepts and measurement of agricultural productivity. Am. J. Ag. Econ. 57(5): 910-915.

Christensen, L.R.; Greene, W.H. 1976. Economies of scale in U.S. electric power generation. J. Pol. Econ. 84(4): 655-675.

Christensen, L.R.; Cummings, D.; Jorgenson, D.W. 1980. Economic growth, 1947-1973: an international comparison. Pages 595-698 in J.W. Kendrick and Vaccara, eds. New developments in productivity measurement and analysis. University of Chicago Press, Chicago, IL.

Christensen, L.R.; Cummings, D. 1981. Real product, real factor input, and productivity in the Republic of Korea, 1960-1973. J. Dev. Econ. 8:285-302

Constantino, L.F.; Haley, D. 1989. A comparative analysis of sawmilling productivity on the B.C. Coast and in the U.S. Douglas fir regions: 1957 to 1982. For. Prod. J. 39(4): 57-61.

Constantino, L.F.; Uhler, R.S. 1987. Interregional and intertemporal differences in North American softwood lumber production costs. For. Econ. and Policy Analysis Res. Unit. Univ. British Columbia, Vancouver, British Columbia. Working Paper 101. 20 p.

Daly, M.J.: Rao, S. 1985. Productivity, scale economies, and technical change in Ontario Hydro. Southern Econ. J. 52(1): 167-180.

DeBrock, L.M. 1985. Market structure, innovation, and optimal patent life. J. Law and Econ., 28(1): 223-244.

Denny, M.; Fuss, M.; May, J.D. 1981. Intertemporal changes in regional productivity in Canadian manufacturing. The Can. J. Econ. 14(3): 390-408.

Denny, M.; Fuss, M.; Waverman, L. 1981. The measurement and interpretation of total factor productivity in regulated industries with application to Canadian telecommunications. Pages 179-218 in T.G. Cowing and R.E. Stevenson, eds. Productivity measurement in regulated industries. Academic Press, New York, NY.

Denny, M.; Bernstein, J.; Fuss, M.; Nakamura, S.; Waverman, L. 1992. Productivity in manufacturing industries, Canada, Japan, the United States, 1953-1986: was the "productivity slowdown" reversed? The Can. J. Econ. 25(3): 584-603.

Department of Finance Canada. 2006. Fiscal Reference Tables 2006: http://www.fin.gc.ca/toce/2006/frt06_e.html

Diewert, W.E.; Nakamura, A.O. 1993. Essays in index number theory vol. I. In D.W. Jorgenson and J. Waelbroeck (eds.) and J. Tinbergen (Hon. ed.). Contributions to Economic Analysis no. 217. North-Holland, Amsterdam. 551 p.

Diewert, W.E. 2000. The challenges of total factor productivity measurement. International Productivity Monitor, 1(1): 45-52..

Diewert, W.E. 2002. The measurement of aggregate total factor productivity growth. University of British Columbia Discussion Paper No. 02-05. 77 p.

Diwan, R.; Chakraborty, C. 1991. High technology and international competitiveness: Praeger Studies in American Industries. Praeger, New York, NY. 267 p.

Essletzbichler, J.; Winther, L. 1999. Regional technological change and path dependency in the Danish food processing industry. Geografiska Annaler, 81 A (3): 179-196.

Forest Products Association of Canada. 2006. Submission to The House of Commons Standing Committee on Finance, 2006 pre-budget consultations. Ottawa, ON, 11p.

Frank, D. L.; Gebremichael, A.; Oum, T.; Trethway, M. W. 1990. Productivity performance of the pulp and paper industry. Can. J. For. Res. 20: 825-836.

Freeman, K.D.; Oum, T.H.; Tretheway, M.W.; Waters, W.G. II. 1987. The growth and performance of the Canadian transcontinental railways, 1956-1981. Centre for Transportation Studies. Univ. British Columbia, Vancouver, B.C. 345 p.

Ghebremichael, A.; Roberts, D. G.; Tretheway, M. W. 1990. Productivity in the Canadian sawmilling industry: an inter-regional comparison. Forestry Canada, Ontario Region, Great Lakes Forestry Centre. Information Report 0-X-411.

Ghebremichael, A.; Nanang, D.M. 2004. Inter-regional comparative measures of productivity in the Canadian timber harvesting industry: a multilateral index procedure. Inf. Rep. NOR-X-391. Northern Forestry Centre, Natural Resources Canada, The Canadian Forest Service, Edmonton. 36 p.

Givon, D. 2006. Factor replacement versus factor substitution, mechanization and asymmetric Harrod neutrality. Available at: http://www.ifw-kiel.de/VRCent/DEGIT/paper/degit_11/C011_028.pdf, accessed on Nov. 16, 2006.

Gordon, R. 1987. Productivity, wages, and prices inside and outside of manufacturing in the U.S., Japan, and Europe. European Econ. Rev. 31: 685-739.

Griliches, Z. 1998. R&D productivity: the econometric evidence. The University of Chicago Press, Chicago. 382 p.

Griliches, Z. 1989. Patents: recent trends and puzzles. Brookings Papers on Economic Activity, Microeconomics, Vol. 1989: 291-330.

Guilkey, D.K.; Lovell, C.A.K.; Sickles, R.C. 1983. Int'l. Econ. Rev. 24(3): 591-616.

Gujarati, D.N. 2003. Basic econometrics (4th ed): international edition. McGraw-Hill Company, Boston. 1002 p.

Harris, R.G. 2002. Social policy and productivity growth: what are the linkages? Discussion Paper Number 11. Industry Canada, Ottawa, ON. 53 p.

Hirsch, P.M.; Gellespie, J.J. 2001. Unpacking path dependence: differential valuations accorded history across disciplines. Pages 69-90 in Raghu Garud and Peter Karnoe eds. Path dependence and creation. Lawrence Erlbaum Associates, Publishers, Mahwah, New Jersey. 417 p.

House of Commons Standing Committee on Industry. 2000. Productivity and innovation: a competitive and prosperous Canada: http://cmte.parl.gc.ca/Content/HOC/committee/362/indu/reports/rp1031680/indy20/04-toc-e.html

Hulten, C.R. 1979. On the "importance" of productivity change. The Am. Econ. Rev. 69(1): 126-136.

Hulten, C.R. 1992. Growth accounting when technical change is embodied in capital. The Am. Econ. Rev., 82(4): 964-980.

Hulten, C.R. 2001. Total factor productivity: a short biography. Pages 1-52 in Hulten, Dean, and Harper eds. New Developments in Productivity Analysis. Studies in Income and Wealth, Volume 63.

Institute for Competitiveness & Prosperity. 2006. Rebalancing priorities for Canada's prosperity. Report on Canada 2006. Toronto, Ontario. 56 p.

Intriligator, M.D. 1965. Embodied technical change and productivity in the United States 1929-958. The Rev. Econ. and Stats. 47(1): 65-70.

Jaffe, A.B.; Richard, G.N.; Stavins, R.N. 2001. Technological change and the environment. Discussion Paper 00-47REV. Resources for the Future, Washington, D.C. 81 p.

Jones, C.I. 1995. R&D-based models of economic growth. The J. Pol. Econ. 103(4): 759-784.

Jones, C.I. 1998. Introduction to economic growth. W.W. Norton & Company, Inc. New York, NY. 200 p.

Jones, C.I. 1995. R&D-based models of economic growth. The Journal of Political Economy, 103(4): 759-784.

Jorgenson, D.W.; Griliches, Z. 1967. The explanation of productivity change. The Review of Economic Studies, 34(3): 249-283.

Jorgenson, D.W. 1990. Tax reform and the U.S. economic growth. The J. Pol. Econ. 98(5), Part 2: S151-S193.

Kaldor, N. 1957. A model of economic growth. The Econ. J. 67(268): 591-624.

Kant, S., Nautiyal, J. C. 1997. Production structure, input substitution, technological change, and total factor productivity in the Canadian logging industry. Can. J. For. Res. 27(5): 701-710.

Kendrick, J.W. 1977. Understanding productivity: an introduction to the dynamics of productivity change. John Hopkins University Press, Baltimore. 141 p.

Kennedy, C.; Thirlwall, A.P. 1972. Surveys in applied economics: technical progress. Econ. J. 11-72.

King, R.G.; Rebelo, S. 1990. The problem of development: a Conference of the Institute for the Study of Free Enterprise Systems. The J. Pol. Econ. 98(5), Part 2: S126-S150.

Knelller, R.; Bleaney, M.F.; Gemmell, N. 1999. Fiscal policy and growth: evidence from OECD countries. J. Publ. Econ. 74(1999): 171-190.

Latta, G. S.; Adams, D. M. 2000. An econometric analysis of the output supply and input demand in the Canadian softwood sawmilling industry. Can. J. For.
Res. 30: 1419-428.

Leibovitz, J.S. 2002. Inventing a nonexclusive patent system. The Yale Law Journal. 111(8): 2251-2287.

Link, A.N.; Siegel, D.S. 2003. Technological change and economic performance. Routlege, NY, New York. 156 p.

Lipsey, R.G.; Carlaw, K.I. 2004. Total factor productivity and the measurement of technological change. Ca. J. Econ. 37(4): 1118-1150

Lipsey, R.G.; Carlaw, K.I.; Bekar, C.T. 2005. Economic transformations, general purpose technologies and long-term economic growth. Oxford University Press, New York, NY. 595 p.

Mankiw, N.G.; Scarth, W. 1995. Macroeconomics, Canadian edition. Worth Publishers, New York, NY. 556 p.

Manning, G. H.; Thorburn, G. 1971. Capital deepening and technological change: the Canadian pulp and paper industry. Can. J. For. Res. 1:159-166.

Manning, G.H. 1972. The utilization of wood residue in Canada. Info. Rep. E-X-13, Forest Economics and Research Institute, Environment Canada, Forestry Service, Ottawa, ON. 25 p.

Martinello, F.; 1985. Factor substitution, technological change, and returns to scale in Canadian forest industries. Can. J. For. Res. 15: 1116-1124.

Martinello, F. 1987. Substitution, technological change and returns to scale in B.C. wood products industries. Applied Econ. 19:483-496.

Maruo, N. 1983. Productivity improvement in Japan: an econometric analysis. Pages 219-265 in Measuring productivity trends and comparisons from the first international symposium, sponsored by the Japan Productivity Center. UNIPUB, New York. 290 p.

Mawson, P.; Carlaw, K.I.; McLellan, N. 2003. Productivity measurement: alternative approaches and estimates. New Zealand Treasury Working Paper 03/12, 33 p.

Meil, J. K.; Nautiyal, J. C. 1988. An intraregional economic analysis of production structure and factor demand in major Canadian softwood lumber producing regions. Can. J. For. Res.18: 1036-1048.

Meil, J.K.; Singh, B.K.; Nautiyal, J.C. 1988. Short-run actual and least-cost productivities of variable inputs for the British Columbia Interior softwood sawmilling industry. For. Sci. 34(1): 88-101.

Morishima, M. 1967. A few suggestions on the theory of elasticity. Econ. Rev. 16: 144-150.

Myers, R.J. 2004. Model specification analysis. Lecture Notes for AEC 835: Introductory Econometrics, Department of Agricultural Economics, Michigan State University, E. Lansing Michigan.

Nadiri, M.I. 1970. Some approaches to the theory and measurement of total factor productivity: a survey. J. Econ. Lit. 8(4): 1137-1171.

Nagubadi, R.V.; Zhang, D.; Prestemon, J.P.; Wear, D.N. 2004. Softwood lumber products in the United States: substitutes, complement, or unrelated. For. Sci. 50(4): 416-426.

Nanang, D.M.; Ghebremichael, A. 2006. Inter-regional comparisons of production technology in Canada's timber harvesting industries. For. Pol. and Econ. 8(2006): 797-810.

Nautiyal, J.C.; Singh, B.K. 1983. Using derived demand techniques to estimate roundwood demand. Can. J. For. Res. 13: 1174-1184.

Nautiyal, J. C.; Singh, B. K. 1985. Production structure and derived demand for factor inputs in the Canadian sawmilling industry. For. Sci. 31: 871-881.

Neuman, W.L. 1997. Social research methods: qualitative and quantitative approaches (3rd ed.). Allyn and Bacon, Boston. 560 p.

Nicholson, W. 2002. Microeconomic theory, basic principles and extensions, 8th ed. Thomson Learning, United States, 748 p.

Nordhaus, W.D. 2002. Productivity growth and the new economy. Brookings Papers on Econ. Activity, Vol. 2002, No. 2: 211-244.

North, D.C. 1993. Institutions, transaction costs and productivity in the long-run. Working Paper No. 9309004, Dept. of Economics, Washington University, St. Louis, Missouri, 10 p.

North, D.C. 2002. Institutions, institutional change and economic performance: political economy of institutions and decisions. (13th reprint). Cambridge University Press, New York, NY. 152 p.

Oum, T.H.; Tretheway, M.W. 1989. Comparison of the productivity performance of the Canadian, U.S., and Sweden pulp and paper industries. Forest Economics and Policy Research Unit, The University of British Columbia, Vancouver, B.C. Working Paper 132. 29 p.

Oum, T.H.; Tretheway, M.W.; Zhang, Y. 1990. Productivity measurement for the pulp and paper industry with adjustment for capacity utilization: a comparison of Canada, Sweden, and U.S. Forest Economics and Policy Research Unit, The University of British Columbia, Vancouver, B.C. Working Paper 143. 33 p.

Oum, T.H.; Yu, C. 1998. Winning airlines: productivity and cost competitiveness of the world's major airlines. Kluwer Academic Publishers, Boston. 220 p.

Parks, R.W. 1971. Price responsiveness of factor utilization in Swedish manufacturing, 1870-1950. The Rev. Econ. & Stats. 53(2): 129-139.

Pearce, D.W. (ed.) 1992. The MIT dictionary of modern economics. The MIT Press, Cambridge, MA. 474 p.

Pessoa, S.A.; Pessoa, S.M.; Rob, R. 2005. Elasticity of substitution between capital and labor and its implications to growth and development. PIER Working Paper 05-012. Penn Institute for Economic Research, Dept. of Economics, University of Pennsylvania. 50 p.

Pierson, P. 2000. Increasing returns, path dependence, and the study of politics. The Am. Pol. Sci. Rev., 94(2): 251-267.

Pindyck, R.S. 1979. Interfuel substitution and the industrial demand for energy: an international comparison. The Rev. Econ. & Stats. 61(2): 169-179

Pindyck, R.S.; Rubinfeld, D.L. 1998. Econometric models and economic forecasts (4th ed.). Irwin-McGraw-Hill, Boston, Massachusetts. 634 p.

Prescott, E.C. 1998. Needed: a theory of total factor productivity. International Economic Review, 39(3): 525-551.

Quadrini, V. 1999. Growth, learning, and redistributive policies. J. Publ. Econ. 74(1999): 263-297.

Rao, P.S.; Preston, R.S. 1983. Inter-factor substitution and total factor productivity growth. Economic Council of Canada, Ottawa, ON. Disc. Pap. 242. 53 p.

Romer, P.M. 1986. Increasing returns and long-run growth. J. Pol. Econ. 94(5): 1002-1037.

Romer, P.M. 1990. Endogenous technical change. The J. Pol. Econ. 98(5): S71-S102.

Romer, D. 1996. Advanced macroeconomics. McGraw-Hill Companies, Inc. New York, 540 p.

Rosegger, G. 1986. The economics of production and innovation: an industrial perspective (2nd ed). Pergamon Press, New York. 275 p.

Ruttan, V. W. 1997. Induced innovation, evolutionary theory, and path dependence:sources of technical change. The Econ. J. 107: 1520-1529.

Ruttan, V.W. 2001. Technology, growth, and development: an induced innovation perspective. Oxford University Press, New York, Oxford. 656 p.

Sato, R. 1977. Homothetic and non-homothetic CES production functions. The Am. Econ. Rev. 67(4): 559-569.

Sharpe, A. 2006. Challenges facing Canada in the areas of productivity, innovation, and investment. Paper presented at a conference held on March 10, 2006 under the theme of "Canada's Competitiveness and Prosperity". Institute for Competitiveness and Prosperity, Ottawa, ON, 15 p.

Sherif, F. 1983. Derived demand of inputs of production in the pulp and paper industry. For. Prod. J. 33(1): 45-49.

Singh, B. K., Nautiyal, J. C., 1986. A comparison of observed and long run productivity of and demand for inputs in the Canadian sawmilling industry. Can. J. For. Res.16: 443-455.

Smith, P.; Munn, I.A. 1998. Regional cost function analysis of the logging industry in the Northwest and Southeast. For. Sci. 44(4): 517-525.

Smolny, W. 2000. Endogenous innovations and knowledge spillovers: a theoretical and empirical analysis. ZEW Economic Studies, Centre for European Economic Research. Phycica-Verlag, A Springer-Verlag Company, Germany. 277 p.

Solow, R.M. 1956. A contribution to the theory of economic growth. The Quarterly J. Econ., 70(1): 65-94.

Solow, R.M. 1957. Technical change and the aggregate production function. The Rev. Econ. and Stats., 39(3): 312-320.

Standing Committee on Industry. 2000. Productivity and innovation: a competitive and prosperous Canada. The House of Commons Canada, Ottawa, ON. 182 p.

Star, S.; Hall, R.E. 1976. An approximation of divisia index of total factor productivity. Econometrica, 44(2): 257-263.

Statistics Canada. 2001. Investment flows and capital stocks methodology. Investment and Capital Stock Division, National Wealth and Capital Stock Section, Ottawa, ON. 31 p.

Statistics Canada. 2006.: http://www.statcan.ca/english/Subjects/Standard/sic/sice80-classe.htm#251

Stevenson, R. 1980. Measuring technological bias. The Am. Econ. Rev. 70(1):162-173.

Stier, J., 1980. Estimating the production technology in the U. S. forest lumber industries. Forest Sci. 26: 471-484.

Studenmund, A.H. 2006. Using econometrics: a practical guide (5th ed.). Pearson Addison Wesley, Boston. 639 p.

Tandon, P. 1982. Optimal patents with compulsory licensing. The J. Pol. Econ. 90(3): 470-486.

Trueblood, M.A.; Ruttan, V.W. 1995. A comparison of multifactor productivity calculations of the U.S. agricultural sector. J. Prod. Anal. 6:321-331.

Varian, H.R. 1984. Microeconomic analysis (2nd ed.). W.W. Norton & Company, New York. 348 p.

White, K.J. 2003. SHAZAM the econometric computer program, version 9, Professional Edition, University of British Columbia: http://shazam.econ.ubc.ca/ .

Wikipedia, the free encyclopedia: http://en.wikipedia.org/path_dependence (accessed Oct. 26, 2006).

Williamson, T.; Hauer, G.; Luckert, M.K. 2004. A restricted Leontief profit function model of the Canadian lumber and chip industry: potential impacts of US countervail and Kyoto ratification. Can. J. For. Res. 34: 1833-1844.

Wolf, E.N. 1996. The productivity slowdown: the culprit at last? Follow-up on Hulten and Wolf. The Am. Econ. Rev. 86(5): 1239-1252.

Wooldridge, J.M. 2006. Introductory econometrics: a modern approach (3rd ed.). Thomson-Southwestern, USA. 890 p.

You, J.K. 1976. Embodied and disembodied technical progress in the United States, 1929-1968. The Rev. Econ. and Stats. 58(1): 123-127.

Zellner, A. 1962. An efficient method of estimating seemingly unrelated regression and tests for aggregation bias. J. Am. Stat. Assoc. 57: 348-368.