CAHIER DE RECHERCHE #1701E
Département de science économique
Faculté des sciences sociales
Université d'Ottawa

WORKING PAPER #1701E
Department of Economics
Faculty of Social Sciences
University of Ottawa

Regional Productivity Convergence: An Analysis of the Pulp and Paper Industries in U.S., Canada, Finland, and Sweden

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January 2017

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Abstract

In this paper we investigate the presence of productivity convergence in eight regional pulp and paper industries of U.S. and Canada over the period of 1971-2005. Expectation of productivity convergence in the pulp and paper industries of Canadian provinces and of the states of its southern neighbour is high since they are trading partners with fairly high level of exchanges in both pulp and paper products. Moreover, they share a common production technology that changed very little over the last century. We supplement the North-American regional data with national data for two Nordic countries, Finland and Sweden, which provides a scope to compare the productivity performances of four leading players in global pulp and paper industry. We find evidence in favour of the catch-up hypothesis among the regional pulp and paper industries of U.S. and Canada in our sample. The growth performance is at the advantage of Canadian provinces relative to their U.S. counterparts. However, it is not good enough to surpass the growth rates of this industry in the two Nordic countries.

Key words: *TFP convergence, multilateral TFP index, pulp and paper industry, translog cost function.*

JEL Classification: C22, F33.

Résumé

Nous analysons la convergence de la productivité totale des facteurs de production(PTF) de l'industrie des pâtes et papiers dans huit régions du Canada et des États-Unis au cours de la période 1971-2005. Nous nous attendons à observer la convergence de la PTF de cette industrie dans les quatre provinces canadiennes et les quatre états américains parce qu'il existe un très haut niveau d'échanges pour les pâtes et pour les papiers et cartons entre ces deux partenaires commerciaux et que les producteurs utilisent une même technologie qui a peu évolué depuis un siècle. Nous ajoutons aussi les informations statistiques de deux pays nordiques, à savoir, la Finlande et la Suède. Ceci nous permet d'étudier l'évolution de la PTF à partir d'observations provenant de quatre pays qui sont parmi les plus grands à l'échelle mondiale. L'information statistique disponible nous permet d'observer un rattrapage des provinces canadiennes et surtout des deux pays nordiques par rapport à l'industrie des quatre états américains. Les industries de la Finlande et la Suède offrent la meilleure performance au chapitre de la croissance de la PTF au cours de cette période.

Mots clés : *Convergence de PTF, indice multilatéral de PTF, industrie des pâtes et papiers, fonction de couts Translog.*

Classification JEL : C22, F33.

1 Introduction

Productivity is one of the major determinants of the competitive position of a national industry in the world market.[1] Chambers and Gordon (1966) argue that under constant returns to scale, productivity of the trade exposed sector determines the wage rate not only of this sector but also of the whole economy. This important indicator has attracted the attention of researchers and academicians who have developed a large literature dealing with various measurement issues,[2] and of national statistical agencies that implement specific programs designed to assess productivity of parts or the whole economy.[3]

The Canadian pulp and paper manufacturing industry is fairly large according to the usual economic indicators and it is one of the major industrial sectors in national and regional economies of Canada. The economic significance of Canadian pulp and paper industry lies on the fact that this industry has always been a net contributor to the balance of payments. In the world market, Canada and U.S. are the two leading players for the pulp and paper industry.[4] Moreover, they are direct competitors, particularly in the U.S. market. The level of integration between the two countries is also very high and both countries are trading partners in cases of both pulp and paper products.

Productivity growth over long periods is primarily determined by the technological advancement in an industry and that advance is highly correlated across nations (Denny et al., 1992). The world pulp and paper industry share a common production technology and the basics of paper making have changed little over the last century (Kuhlberg, 2015). At the first stage, wood fiber that is the main raw material is freed

[1] Other local factors such as taxation and government regulations also play a role in this respect.

[2] For a brief survey, see Hulten (2001).

[3] OECD provides guidance to member countries in this endeavour. See OECD (2011).

[4] According to the most recent statistics published by F.A.O. (2013), U.S. is the leading producer of wood pulp, accounting for almost 30 percent of total world production, followed by Canada which accounts for almost 11 percent of the global production. In case of paper and paperboard production both U.S. and Canada are among the top five producers in the world and they jointly account for 22 percent of total world production. In both type of products, they are among the top five exporting countries.

from raw wood through chemical and/or mechanical processes to yield pulp, and at the second stage, the mixture is spread over a rolling screen to be dried and to obtain various paper and cardboard products. Mill owners purchase their equipment form a very small group of manufacturers that serve the world market and they are the main innovators in this industry. According to Ghosal (2009), the U.S. pulp and paper industry perform little R&D and its R&D intensity (0.5 percent) is one of the lowest among U.S. manufacturing industries.[5] Three major challenges that the pulp and paper industry in industrialized countries faced since the early seventies are: First, the oil crisis of the seventies opened the way to other energy sources including biomass use. Second, fiber supply changed from round wood to wood chips, and recycled paper brought a growing contribution. Third, governments enforced more stringent environmental regulations on water and air emissions.

The above discussion makes it clear that we have two leading players of the global pulp and paper industry which share a common production technology that changed little during the last century and are trading partners with high level of exchanges in both pulp and paper products. Furthermore, they compete on the world market for fairly homogeneous products. Such a setting should lead to total factor productivity (TFP) convergence. While multiple reasons to expect TFP convergence between the pulp and paper industries in Canada and U.S. are present, productivity performance of the industry may or may not be uniform even across regions within a country.

In this paper we analyze the productivity performance of the pulp and paper industries in Canada and the U.S. over the period extending from 1971 to 2005 by taking advantage of regional disaggregated data on four Canadian provinces — Alberta, British Columbia (BC), Ontario, and Québec — and on four U.S. states — Georgia, Illinois, Maine, and Washington. Canada and U.S. have huge forestlands that support diverse forestry due to soil and climate conditions, and hence the wood fiber supply differ significantly from one region to the next. Furthermore, most of the forestlands

[5]The R&D intensity of the Canadian pulp and paper industry was 0.6 percent in 2008.

in Canada are owned by the provinces[6] that have their own forestry regime to provide access to industrial uses, and that apply their own environmental regulations. In order to take the diversity of conditions at the regional level into consideration, we build our sample to include the four largest Canadian forestry provinces, and the U.S. states are selected to represent regional industry conditions as well as to represent the industry of similar size. The use of regional disaggregated data allows us to investigate whether the regional industries within a country follow a uniform path over the course of time. Moreover, this also allows us to investigate the presence of convergence in terms of TFP in the pulp and paper industry.

We supplement the North American regional level data with national data for two Nordic countries — Finland and Sweden. The inclusion of Finland and Sweden is justified in the sense that this gives us the opportunity to compare performances of the North American regions with those of others who are competing with them in the global market.[7] Furthermore, the input mix is disaggregated into five components — labour, capital, materials, electricity, and other energies, which are mostly fossil fuels. To the best of our knowledge there are only three studies available that investigate the productivity performance of the pulp and paper industry at regional levels in Canada (see Denny et al., 1981; Hailu, 2003; Shahi et al., 2011) and there is no empirical study that examines the performance of this industry at regional levels in U.S.

In order to estimate TFP, in this paper we employ two widely used methods of productivity measurement — the index number technique and the econometric estimation approach. With the index number technique we exploit an extension of the transitive multilateral productivity index (Caves et al., 1982b) by using the relationship between the price indexes of output and inputs and the translog cost function. The econometric approach involves estimation of a translog system that allows non-neutral technical

[6]Public forestland ownership in the four provinces in our sample ranges from 90 percent in Québec to approximately 100 percent in Alberta and BC.

[7]According to F.A.O. (2013), in 2011, both Finland and Sweden were among the top five leading paper and paperboard exporters in the world. They jointly account for 13 percent of global wood pulp production which places them among the top five producers in the world.

change. Following Jin and Jorgenson (2010) we decompose the TFP growth rate into autonomous and induced technical change components. The use of direct parametric estimation enables us to provide estimates of price elasticities and of factor biases to technical change. We also provide confidence intervals of our elasticity estimates.[8]

Keay (2003) provides Canadian relative to American TFP ratios for nine manufacturing industries covering the first ninety years of the twentieth century. He finds little evidence of productivity gap on behalf of the Canadian manufacturers and concludes that the Canadian manufacturers were equally productive as their U.S. counterparts during the sample period. The pulp and paper industry, which is by far the largest industry in his sample, displayed an above average performance.

Our findings do not support the productivity assessment of Keay (2003) for the pulp and paper industry in Canada and U.S. over the more recent period. Although TFP grew at a higher rate in the Canadian provinces, the levels were lower in Canada than the levels of the leading performers in U.S. during the sample period. Overall, Finland and Sweden had the best TFP growth performance while Illinois experienced the worst in this respect. Moreover, based on our results we find evidence of productivity convergence taking place across the pulp and paper industries in U.S. and Canada.

The rest of the paper is organized as follows. Section 2 provides a review of the existing literature. Section 3 presents the theoretical background of the productivity estimation approaches used in this study. Section 4 describes the dataset while Section 5 discusses the results. Finally, Section 6 adds some concluding remarks.

2 Literature Review

Although the pulp and paper industry is of significant importance to the regional economies of several industrialized countries, there have only been a limited number

[8]For a discussion on the importance of parameters of the elasticity of substitution and the direction of technical change, see León-Ledesma et al. (2010).

of studies that look into the productivity performance of this industry using regional level data. Moreover, existing studies differ in terms of productivity measurement approaches, number and the measure of output(s) and inputs, and the coverage of sample periods. Denny et al. (1981) examine the growth rates of TFP for twenty Canadian manufacturing industries, including the paper industry, covering the period of 1961–75 in four regions of Canada — BC, Ontario, Québec, and the 'Rest of Canada'. Their estimated annual TFP growth rates vary between 0.80–1.04 percent across regions. Hailu (2003) compares the TFP growth rates in four regions of Canada — Ontario, Québec, BC, and the Atlantic and Prairie region — for the period of 1970–93. His results indicate that the productivity of pulp and paper industry in those regions were decreasing by 0.85 percent per year. Shahi et al. (2011) is the other regional study, and it estimates negative TFP growth rates, -0.5 to zero percent, for the pulp and paper industry in Ontario during 1967–2003. To the best of our knowledge, there is no empirical study that examines the productivity performance of regional pulp and paper industries in U.S.

A few other studies examine the productivity performance at the national level. Studies on the Canadian pulp and paper industry include Sherif (1983), Martinello (1985), Nautiyal and Singh (1986), and Frank et al. (1990). Estimated annual growth rates of TFP varies from 1.2 to 2 percent across these studies. For the U.S. industry, Borger and Buongiorno (1985) estimate TFP growth rates of paper and paperboard industries for the period of 1958–81. Their estimated TFP growth rate for paper is 2.89 percent or 4.54 percent, depending on the index, while it is slightly over 1 percent for paperboard.

A set of other studies compares the productivity performances of pulp and paper industries in U.S. and Canada. For example, Denny et al. (1992) provide a comparison of TFP growth rates in the paper industries of Canada, U.S., and Japan for the period of 1953–86. According to their results, during the period of 1973–86 the average annual growth rate of TFP for U.S. paper industry is 0.78 percent while the Canadian paper industry has a negative growth rate, -0.01 percent.[9] Hseu and Buongiorno (1994) estimate 0.5 percent annual TFP growth rate for this Canadian industry during 1959–1987 while it is 0.7 percent for its U.S. counterpart. Moreover, Hseu and Shang (2005) examine the productivity of pulp and paper industry in OECD countries over 1991–2000. According to their results the industry in Canada was enjoying an average annual growth rate of 2 percent while that in U.S. had almost no growth rate, 0.2 percent per year. Among the Nordic countries, the pulp and paper industry in Sweden had 1.5 percent growth per year while that in Finland was growing at 1.2 percent.

Results on relative TFP levels are more uniform than the results on TFP growth rates across studies. For example, Denny et al. (1992) also provide a relative Canada-U.S. TFP comparison for three sub-periods: 1964–66, 1974–76, and 1983–85. Paper and lumber are the only two industries in which Canadian manufacturers were more productive than their American counterpart in all the three sub-periods. Superior relative TFP level performance of Canadian pulp and paper industry is also confirmed by Keay (2000, 2003). Both studies find that the Canadian paper industry is more productive than its American counterpart.

All of the above mentioned studies use conventional TFP measures in the sense that they only use marketable outputs while calculating TFP. However, Hailu and Veeman (2000, 2001) introduce a productivity measure which accounts for the undesirable pollutant outputs and yields higher TFP estimates relative to the conventional measures. The TFP growth rates of Canadian pulp and paper industry in their studies for the period of 1959–94 varies from -0.15 percent to 2.1 percent depending on the estimation technique.

Based on the findings of existing literature it is clear that the estimates of TFP growth rates varies across studies. Findings on the direction of factor biases to technical change as well as the substitution possibilities among factors of production also vary

[9]This sub-period is chosen to facilitate a comparison of their estimates of TFP growth rates with the ones calculated in the present study. This is the most suitable sub-period in their sample periods for which we can compare our results with.

across studies that rely on explicit functional forms. See, for example, Sherif (1983), Martinello (1985), Nautiyal and Singh (1986), Borger and Buongiorno (1985), and Shahi et al. (2011), among others. One obvious explanation of this variation in results could be the difference in the coverage of sample periods. However, the difference also holds when comparable study periods are used. Methodological difference may be another source of variation in TFP estimates across studies. In this study, we make use of two widely used approaches to productivity measurement – index number and econometric estimation of the translog cost function. In what follows, we briefly discuss the theoretical background of the measurement approaches before presenting our data and estimation results.

3 Theoretical Background

Two most frequently used approaches to productivity measurement are the index number technique and econometric estimation.[10] With the index number approach, rate of change in TFP indexes are calculated as a measure of productivity growth, and the most commonly used index is the Tornqvist-Theil index. Econometric estimation, on the other hand, can be done by using either a production function or a cost function. First, the production or the cost function is estimated econometrically and then it is differentiated with respect to time. Under constant returns to scale this gives the productivity growth rate. Moreover, if we assume that the function takes the translog functional form then, together under the assumptions of profit maximization for production function (or cost minimization for cost function) and of perfect competition in factor markets, both the Tornqvist index number and econometric estimation approaches would provide similar TFP growth rates. The correspondence between Tornqvist and the translog is well established by Diewert (1976) and Caves et

[10]See Feng and Serletis (2008) for a discussion on various approaches to productivity measurement, and Van Biesebroeck (2007) for a comparison of productivity estimates obtained from different measurement approaches.

al. (1982a).[11] Although a set of studies uses other flexible functional forms, translog is the most frequently used flexible functional form in studies assessing production technology and technical change (Dissou and Ghazal, 2010).

In this study we calculate TFP growth rates by using both the index number and econometric estimation approaches. With the index number approach we extend the correspondence established by Caves et al. (1982b) between Tornqvist quantity index of productivity and translog production function to Tornqvist price index of productivity and translog cost function that allows for transitive and multilateral TFP comparisons. With the econometric estimation method we estimate a translog cost system of equations. Constant returns to scale is assumed in both approaches.

3.1 Index Number Approach

We assume that the industry is operating under perfect competition in both product and factor markets, and that the production technology is characterized by constant returns to scale. Under these conditions, we have the equality between output price and unit cost,

$$p_{yt}^k = c^k(\mathbf{p}_t^k) \tag{1}$$

where p_{yt}^k is the price of output in region k $(k = 1, ..., K)$ at time t, $c^k(\mathbf{p}_t^k)$ is the well behaved unit cost function in region k at time t, and $\mathbf{p}_t^k$ is the vector of input prices, p_{it}^k, for inputs i $(i = 1, ..., n)$ in region k at time t.

We assume that the unit cost function in (1) has the translog functional form as

[11] Diewert (1976) describes the relationship between the estimation of production technology and the measurement of productivity index in terms of exact and superlative index numbers. An index number is exact for a particular functional form if the index of outputs between any two periods is identically equal to the ratios of output obtained from the functional form. He classifies an index number as superlative if it is exact for a second order aggregator function. As shown by Caves et al. (1982a), if technology can be represented by the translog transformation function then under the assumption of constant returns to scale and profit maximization the index number technique of calculating productivity must be exact for the translog. Tornqvist indexes are superlative for the linear homogenous translog aggregator function.

follows,

$$\ln c^k(\mathbf{p}_t^k) = \alpha_0^k + \sum_i \alpha_i^k \ln p_{it}^k + \frac{1}{2}\sum_i \sum_j \alpha_{ij} \ln p_{it}^k \ln p_{jt}^k \tag{2}$$

where $\alpha_{ij} = \alpha_{ji}$, for $i \neq j$. The translog cost function in (2) is assumed to satisfy the properties of a well behaved cost function, in particular, it is nonnegative and non-decreasing, linear homogeneous, and concave in p_{it}^k. Linear homogeneity in prices implies that,

$$\sum_i \alpha_i^k = 1, \text{ and } \sum_j \alpha_{ij} = 0, \qquad \text{for } i = 1, ..., n. \tag{3}$$

The translog functional form in equation (2) allows for some specific regional characteristics in the linear terms, and hence allows for non-neutral technological change.

Following the same development as Caves et al. (1982b), under constant returns to scale and profit maximization with perfectly competitive markets, the relationship that they established between Tornqvist output and input quantity index and the translog transformation function can be extended to the relationship between Tornqvist output and input price index and the translog cost function. This leads to the following TFP formula:

$$\ln \lambda_t^k = \frac{1}{2}\sum_i \left(S_{it}^k + \overline{S_i}\right)\left(\ln p_{it}^k - \overline{\ln p_i}\right) - \left(\ln p_{yt}^k - \overline{\ln p_y}\right) \tag{4}$$

where λ_t^k represents the productivity level of region k at time t, S_{it}^k is the cost share of factor i in region k at time t, $\overline{\ln p_y}$ is the average of $\ln p_{yt}^k$ over regions and time, $\overline{S_i}$ is the average of S_{it}^k over regions and time, and $\overline{\ln p_i}$ is the average of $\ln p_{it}^k$ over regions and time.

Equation (4) provides a transitive multilateral TFP index which enables us to compare the TFP of region k at time t relative to the overall average over all regions and time periods in the sample. It is independent of the choice of a particular region or time period as a basis for comparison. However, it is dependent on the available sample.

3.2 Econometric Technique

For econometric estimation, we assume that the unit cost function in (2) takes the translog functional form (Christensen et al., 1971, 1973) as follows,

$$\ln c(\mathbf{p}) = \alpha_0 + \sum_i \alpha_i \ln p_i + \frac{1}{2}\sum_i \sum_j \alpha_{ij} \ln p_i \ln p_j + \sum_i \alpha_{it} t \ln p_i + \alpha_t t + \frac{1}{2}\alpha_{tt} t^2 \quad (5)$$

where $i, j = 1, ..., n$.[12] Technical change is assumed to be non-neutral and is modelled through time trend, t.[13] Corresponding input cost share equations can be obtained by using Shephard's Lemma after logarithmic differentiation of the unit cost function (5) with respect to input prices,

$$S_i = \alpha_i + \alpha_{ii} \ln p_i + \sum_{j \neq i} \alpha_{ij} \ln p_j + \alpha_{it} t. \quad (6)$$

Homogeneity and symmetry restrictions imply the following constraints

$$\sum_{i=1}^{n} \alpha_i = 1, \quad \sum_{i=1}^{n} \alpha_{ij} = \sum_{j=1}^{n} \alpha_{ij} = \sum_{i=1}^{n} \alpha_{it} = 0. \quad (7)$$

Necessary and sufficient condition for concavity is that the Hessian matrix of the cost function (5) be negative semidefinite, which according to Diewert and Wales (1987) implies that

$$\mathbf{H} = \mathbf{A} - \mathbf{S}^n + \mathbf{S}\mathbf{S}' \quad (8)$$

be negative semidefinite, where $\mathbf{A} = [\alpha_{ij}]$ is the $n \times n$ symmetric matrix of α_{ij}, $\mathbf{S} = [S_1, ..., S_n]'$ is the vector of input shares, and $\mathbf{S}^n$ is the $n \times n$ diagonal matrix of the shares.

[12] For notational simplicity we suppress the region superscript and time subscript.

[13] Assumptions of neutral and no technical change can be tested directly. If $\alpha_{it} = 0$ for all i, then technical change is neutral, and if $\alpha_t = \alpha_{tt} = \alpha_{it} = 0$ for all i, then there is no technological progress.

TFP is estimated as,

$$TFP = -\frac{\partial \ln c(\mathbf{p}_t)}{\partial t} = -\left(\alpha_t + \alpha_{tt} t + \sum_{i=1}^{n} \alpha_{it} \ln p_i\right). \tag{9}$$

A reduction in unit cost due to technological progress will translate into a positive TFP growth. As technical change is modelled through time trend, α_t captures the rate of pure technical change while the second part on the right hand side measures its acceleration rate. Together the first two parts on the right hand side, gives us the rate of unit cost reduction due to autonomous or unbiased technical change. The last part measures the contribution to TFP growth due to the biased effect of technical change on factor cost shares. The coefficients α_{it} represent the rates of input bias due to technical change. With regards to the direction of bias, a positive (negative) α_{it} would indicate a technical change that is factor i using (saving).

Furthermore, we use the estimated parameters and fitted values of factor shares to calculate the price elasticities of factor demand. Own- and cross-price elasticities are calculated as follows,

$$\eta_{ij} = \frac{\widehat{\alpha}_{ij} + \widehat{S}_i \widehat{S}_j}{\widehat{S}_i}, \qquad \text{for } i \neq j, \tag{10}$$

$$\eta_{ii} = \frac{\widehat{\alpha}_{ii} + \widehat{S}_i^2 - \widehat{S}_i}{\widehat{S}_i}, \qquad i, j = 1, ..., n, \tag{11}$$

where all other factor prices are fixed.

It is to be noted that the elasticity estimates are not the estimated parameters of the system. Rather, they are nonlinear functions of the estimated parameters and fitted shares, and as a result, the statistical properties of those elasticity estimates are often not known. The traditional method of dealing with this problem involves the use of classical statistical procedure after linear approximation.[14] However, Krinsky and Robb (1986) criticize the use of traditional approach to derive the empirical dis-

[14] For a list of earlier studies using this procedure, see Krinsky and Robb (1986).

tribution of the elasticity estimates, and instead, they suggest the use of simulation technique for deriving statistical properties. They show that the traditional approach is a poor substitute for their proposed simulation technique. One alternative technique, suggested by Efron (1979, 1982), is the use of bootstrap procedure to estimate the empirical distribution of the parameters. Krinsky and Robb (1991) compare the three approaches using two different data sets and show that the results obtained using bootstrap and their specific simulation are similar. They suggest the use of simulation technique on the ground of ease of application.

In this study we compute 95% confidence interval for the elasticity estimators using the method suggested by Krinsky and Robb (1986). This procedure involves generating samples of estimated parameters of the model by taking random drawings from a multivariate normal distribution with the means and variance-covariance matrix of the estimated parameters. The central assumption here is that the estimates of parameters of the model follow their multivariate normal distribution as a limiting case. Then using the generated sample of parameter estimates, elasticity is calculated for each drawing and these simulated elasticity estimates are used to derive the statistical properties. To build the confidence interval, we take 10000 random draws.

4 Data

The dataset used in this study includes data for the pulp and paper industry in four countries — Canada, the United States, Finland, and Sweden — and covers the period from 1971 to 2005.[15] Canadian data are collected at the provincial level, for four provinces, namely, Alberta, British Columbia, Ontario, and Québec, whereas for U.S. data are collected for four states, Georgia, Illinois, Maine and Washington. The U.S.

[15]The sample ends in 2005 due to data availability and also due to the major structural change that accelerated at that time. According to the information provided by the Forest Products Association of Canada (FPAC), 159 pulp and paper mills operated in Canada in 2005. The number fell to 85 in 2013. The downward spiral over such a short period hit particularly newsprint which has been staple in Canada.

states are representative of the four major producing areas – south, north-central, east, and west. National level data are used for Finland and Sweden. The data set contains annual information on prices and values of total output and also on the prices and quantities of five inputs used in the analysis of this study — capital (K), labour (L), materials (M), electricity (E), and other energy (F). Other energies are mainly fossil fuels (coal, natural gas, and refined petroleum products). Data come from official government publications of respective countries and the annual survey of manufacturers is the major source of data for each country. Detailed description of sources of data and the construction of the sample used in this study are presented in Appendix A.

Table 1 presents data on output and inputs of the ten regions in our sample. It can be seen that Sweden had the largest output in 1971 while Alberta had the smallest. Finland had the largest output in 2005. Average annual growth rates of output over the sample period vary to a large extent, ranging from high such as 4.84 percent in Alberta and 3.77 percent in Finland to low such as -0.46 percent in Illinois. Finland and Sweden were parts of the fast growing regions followed by Canadian provinces while U.S. states were trailing.

Given our focus on TFP, here are the observations that can be formulated with respect to factor use over the sample period: First, capital stock grew in all regions except in BC. Second, the use of labour input declined in all regions except in Alberta. Third, materials use increased in all regions except in Illinois and Maine.[16] Moreover, the use of electricity went up everywhere except in Washington. Finally, the use of other energy, mostly fossil fuels, decreased in five regions while it increased in the other five regions.

Table 2 shows information on input prices, their real changes over the sample period, and average input cost shares. Real return to capital decreased in six regions

[16]Total output in Illinois declined during the sample period while it stayed more or less constant in Maine.

while it increased in the other four regions.[17] Real wage, in general, increased in all regions. The evolution of electricity prices is quite diverse across regions, even within the same country. Prices of other energies increased in all regions. This is expected, particularly after the oil crisis of the seventies. Average input cost shares fall within the same range across the regions. Material inputs, on average, have the largest share (almost 54 percent) in total cost of production. Capital and labour bring similar contributions while electricity and other energy shares are quite small.

5 Results

5.1 Index Number Technique

Multilateral productivity index generated by the application of formula (4) is reported in Table 3. Annual TFP levels and the average annual growth rates of TFP for all regions during the sample period are reported in the table. As mentioned earlier, the distinctive feature of the index is multilateral transitivity, that is the productivity figures are comparable across both time and regions, and as a result they are free of the choice of a particular year or a region as a basis of comparison.

The TFP index in Table 3 reveals some interesting insights of productivity patterns among the sample regions. The U.S. states, Georgia and Maine, appear to be consistently more productive than any other regions throughout the whole time period. They are the leaders in terms of TFP levels. However, the growth performance is at the advantage of the Canadian provinces over the U.S. states. On average, the Canadian provinces were enjoying 0.42 percent TFP growth rate while the U.S. states had 0.28 percent. However, this superior growth performance is not large enough to make one of the provinces to become a leader. There is not a single year when the best performance is associated with one Canadian province. The pulp and paper industry

[17]Returns to capital is the residual obtained by netting out the labour cost from value added. It includes return to equity, bond, capital depreciation, and business taxes.

in Canada has been catching up but was still trailing in 2005. Our findings do not support the results provided by Keay (2000, 2003). He finds that the Canadian pulp and paper industry was more productive than their U.S. counterpart during the period of 1971–90.

For regional pulp and paper industries, the only available Canadian studies which we can compare our results with are Denny et al. (1981), Hailu (2003), and Shahi et al. (2011). Our TFP growth rate figures are considerably different than those reported in Denny et al. (1981) when we consider overlapping time periods, 1971–75. Our results also do not support the findings of Hailu (2003) and Shahi et al. (2011). To our knowledge, there is no state level TFP estimate available for the U.S. pulp and paper industry to compare our results with. In comparing our results with those of other studies done for the national pulp and paper industry, the following studies deserve some attention. Hailu and Veeman (2000) report 0.41 percent annual average growth rate of productivity in the Canadian pulp and paper industry. We find similar result, 0.42 percent, for this Canadian industry if we take the mean TFP growth rate of the Canadian provinces in our sample. However, our results are different from those reported in Denny et al. (1992) even if we consider the common time period, 1973–86.

Overall the TFP growth scenario in the pulp and paper industry during the period of 1971–2005 is marked by the dramatic improvement in Nordic nations as well as the dismal performance of the U.S. state, Illinois. Finland has the highest average annual growth rate, 1.18 percent, while productivity was growing by 0.76 percent per year in Sweden.

Although not reported for brevity, we also calculate TFP using the translog multilateral index, proposed by Caves et al. (1982b), that uses the relationship between Tornqvist quantity indexes of output and inputs and the translog transformation function.[18] One important distinction between the two techniques is the use of physical

[18] TFP is measured as: $\ln \mu_t^k = \left(\ln y_t^k - \overline{\ln y}\right) - \frac{1}{2}\sum_i \left(S_{it}^k + \overline{S_i}\right)\left(\ln x_{it}^k - \overline{\ln x_i}\right)$, where μ_t^k represents the productivity level of region k at time t, y_t^k is the output of region k at time t, S_{it}^k is the cost share of factor i in region k at time t, x_{it}^k is the input i in region k at time t, $\overline{\ln y}$ is the average of $\ln y_t^k$

output and input data in the transformation function technique whereas the cost function technique that we employ uses the prices of output and inputs. As the price indexes of output are not available at the level of disaggregation used in this study, we use the national price indexes of output for all provinces and states of Canada and U.S., respectively. One might expect a bias in the productivity estimates generated using the cost function technique as there is no variation in the price indexes of output among the Canadian provinces as well as among the U.S. states. However, similar results obtained from the transformation and cost function techniques assure the existence of single product markets in the pulp and paper industry in Canada and in the U.S. Simple correlation coefficient between the two series is almost one for all regions.

5.2 Translog Cost Function

After imposing the restrictions in (7) on the cost function (5), we estimate the translog systems of equations – the unit cost function (5) jointly with the input cost share equations (6). Error disturbances are added to the equations in the system and are assumed to have a multivariate normal distribution with zero mean and constant covariance, Ω, over time. We delete the material share equation from the system of equations to be estimated in order to avoid the problem of singularity.

We use the iterative Zellner's technique for Seemingly Unrelated Regression (SUR) to estimate the translog system of equations for each region separately. To check for whether the estimated cost function satisfies the concavity property, we compute the eigenvalues of the estimated Hessian matrix (8) at each data point in the sample as well as at the mean of the data. Coverage of concavity by the estimated cost function for each region is reported in Table 4. It can be seen that without restriction concavity coverage is very low. To overcome the problem of little or no concavity coverage by the estimated cost function we impose local concavity on the cost function by using

over regions and time, $\overline{S_i}$ is the average of S_{it}^k over regions and time, and $\overline{\ln x_i}$ is the average of $\ln x_{it}^k$ over regions and time.

the procedure suggested by Ryan and Wales (2000). The procedure is described in detail in Appendix B. We use the nonlinear iterative SUR technique to estimate the system of equations since imposition of local concavity makes the system nonlinear in parameters. Although not perfect, this yields a large improvement in the coverage of concavity. We report the estimation results that yield the best coverage in terms of concavity.

Tables 6 and 7 report the estimated coefficients of nonlinear system of equations (restricted for local concavity) for all regions. Almost all parameter estimates are statistically significant at 1% level of significance. Estimates of α_i represent the mean factor shares at time zero when input prices are normalized to one. Estimated mean factor shares are positive for all inputs in all regions. Moreover, the fitted cost shares are positive at all data points implying that the input demand functions are all strictly positive. Actual and fitted shares correspond very closely. The α_{ij} parameters that are often termed as share elasticities capture how the demand for inputs response to the changes in input prices. They are used in calculating the elasticity estimates.

We perform two tests related to technical change – first, we test for the presence of technical change, and second, we test whether the technical change is neutral. Results from the likelihood ratio tests are presented in Table 5. Possibilities of the absence of technical change and the presence of neutral technical change are rejected at 1% level for all regions in the sample. We also test whether the Canadian provinces (U.S. states) share the same cost function. Possibility of pooling data for Canadian provinces and for U.S. states is rejected at 1% level in both cases.

Own and cross price elasticities of factor demand along with their confidence intervals are reported in Tables 8 through 10. Elasticities are calculated at the mean of the data.[19] All estimated own price elasticities of demand have the correct sign which is also confirmed by the reported confidence intervals. We find the factor demands

[19] Although not reported, we also compute the price elasticites of factor demand when concavity is not imposed. All elasticity estimates, when concavity is not imposed, are very close to the ones reported in Tables 8.

inelastic in all regions as the estimated own price elasticities are below one in absolute terms. This indicates a vulnerability of the industry to any policy change that would impact the factor prices. We find the demand for electricity as much more responsive to price changes than the demand for any other factors in all Canadian provinces with the exception of Québec where labour appears to be the most elastic factor. This is not surprising as historically Québec enjoys one of lowest electricity prices in North America and as a result the pulp and paper industry in Québec has not developed its ability to cope with the rise in electricity price. However, capital is the most elastic factor in U.S. states.

Estimated cross price elasticities of demand suggest that capital and labour are complements in most regions. However, the absolute values are very low and the confidence intervals span positive and negative values. Moreover, we do not find any clear substitution possibility between electricity and other energy. Elasticity estimates of substitution possibility between materials and other inputs are of critical importance for this industry as materials account for more than fifty percent of the total production cost. Our elasticity estimates indicate substantial substitution possibilities between materials and other inputs. In particular, capital and materials are very strong substitutes in the U.S. They are also quite substitutable in Canada, Finland, and Sweden.

Table 11 presents the input biases of technical change which represent the impacts of changes in technology on factor shares over time. They provide us with the information about how the input demand is reacting due to technical change holding the prices of all inputs constant. We find technical change is universally labour saving and in most regions it is other energy saving. However, it is capital, electricity, and materials using in most regions.

Table 12 reports the average annual productivity growth rates obtained by using the estimated translog parameters in (9). The average TFP growth rates are not identical to the rates presented in Table 3, however, they generally provide more or less the same ranking. Table 12 shows also the contribution of autonomous and factor biased technological change to the overall TFP growth. Factor using technological change combined with decreasing input prices and factor saving technological change coupled with an increase in input prices contribute to higher productivity. The converse happens when the direction of factor biases to technological change is reversed. Except for BC, Maine, and Sweden, the contribution of factor biases to technological change is quite significant. Almost all regions in our sample had positive autonomous technical change during the 1971–2005 period, with the exception of Illinois and Washington. In fact, Illinois and Washington are the regions that experienced negative total factor productivity growth rates. Finland and Sweden are the leaders in terms of average annual TFP growth rates, with 1.20 and 1.08 percent, respectively. Among the Canadian provinces BC, with 0.46 percent, has the highest growth rate while Maine had the highest growth rate, 0.37 percent per year, among all U.S. states.

5.3 Productivity Convergence

As discussed in Section 1, there exists several reasons to expect TFP convergence between the pulp and paper industries in U.S. and Canada. Results from the TFP index in Table 3 reveal that the standard deviation of TFP across all regions in our sample, including Finland and Sweden, is declining over time.[20] The ratio of $\left(\frac{\text{Standard Deviation}_{2005}}{\text{Standard Deviation}_{1971}}\right)$ is 0.61 for these ten regions. However, the standard deviation of TFP depicted the opposite trend when we consider only the U.S. and Canadian regions in our sample. Moreover, the ratio of $\left(\frac{\text{Standard Deviation}_{2005}}{\text{Standard Deviation}_{1971}}\right)$ for these eight regions is 1.19. Given the obvious contribution of Finland and Sweden to convergence, we restrict our analysis to U.S. and Canadian regions only.

There is a large literature dealing with industry TFP convergence across regions and countries. For a brief review of studies on industry TFP convergence, see Ball et al. (2004). In order to test the existence of TFP convergence, in this paper we adapt

[20]This is often referred to as σ–convergence.

the methodology proposed by Ball et al. (2004) who analyzed TFP convergence in the agricultural sector across U.S. states from 1960 to 1999. In particular, we estimate the following specification:

$$\widehat{TFP}_t^i = \beta_0 + \beta_1 \ln TFP_{t-1}^i + \beta_2 \left(\frac{\widehat{K}}{L}\right)_t^i + \beta_3 \left(\frac{\widehat{M}}{L}\right)_t^i + \beta_4 \left(\frac{\widehat{F}}{L}\right)_t^i + \beta_5 \left(\frac{\widehat{E}}{L}\right)_t^i + \epsilon_{it} \quad (12)$$

where, TFP_t^i is the total factor productivity for province or state i at time t, $\left(\frac{j}{L}\right)$ are the intensities of factors $j = K, M, E, F$, relative to labour (L), and the hat $(\widehat{\ })$ denotes the growth rate.

Specification (12) allows to test two hypotheses — the catch-up hypothesis and the embodiment hypothesis. While the catch-up hypothesis suggests that the regions with lower TFP at the beginning would display higher rates of productivity growth,[21] the embodiment hypothesis implies that the TFP growth rates will be positively correlated with the growth rates of factors of production.

In estimating (12) we use three-year moving averages for calculating the growth rates. Moving averages are performed to smooth the noise in annual data as displayed in Table 3. Taking the advantage of a larger sample size and longer time periods, Ball et al. (2004) used a five-year moving average. A smaller sample leads us to use three-year moving average. In addition, we perform the panel unit root test suggested by Im et al. (1997) to detect the presence of non-stationarity in time series variables that could cause spurious regression. Results from estimating (12) and the panel unit root test are reported in Table 13. The null hypothesis of a unit root is rejected for each series in the panel, and hence we proceed to the estimation of equation (12) without further transformation.

As expected, the coefficient of $\ln TFP_{t-1}$ is negative and highly significant, con-

[21] This is often referred to as conditional β–convergence. Based on the results of σ– and β–convergence for a group of 14 OECD countries, Van Biesebroeck (2009) finds the presence of productivity convergence during 1970–1999 in almost all industries. He estimates β–convergence for each industry by regressing the productivity growth on the logarithm of initial productivity level pooling all countries.

firming the presence of technological catch-up. All the embodiment coefficients are statistically significant. However, positive and significant coefficients for $\left(\widehat{\frac{M}{L}}\right)$ and $\left(\widehat{\frac{E}{L}}\right)$ imply that the embodiment of technology in materials and electricity are important sources of productivity growth for this industry during the sample period. Overall, capital and materials brought much larger contribution relative to other energies and electricity, although the negative sign attached to the growth rate of capital is not expected. However, we must keep in mind that the pulp and paper industry was subjected to strict regulations with respect to water and air emissions during the sample period. A large share of capital expenditures had to be devoted to satisfy the growing environmental constraints, thus reducing the contribution to the standard measure of TFP growth.

6 Conclusion

In this paper we use regional disaggregated data for the pulp and paper industries in Canada and U.S. to investigate the presence of TFP convergence over the sample period of 1971–2005. National data for Finland and Sweden are added as complements which provides a scope to compare the productivity performances of four leading players in global pulp and paper industry. Although the TFP growth performance is at the advantage of Canadian provinces relative to their U.S. counterparts, the pulp and paper industry in Canada was still trailing the U.S. leaders at the end of the sample period in terms of TFP levels. Moreover, the TFP growth in Canadian provinces is significantly less than the growth this industry enjoyed in Nordic countries. TFP convergence in this industry is expected given the existence of world market for pulp and paper products, the high level of exchanges between U.S. and Canada, and a common technology that has evolved little over the last century. The empirical evidence that we gather is in favour of TFP convergence – the Canadian regions that had lower TFP levels at the start of the sample period caught up to the high performance regions in the U.S.

Convergence of TFP translated into benefits to workers in the regions of high TFP growth since the simple correlation coefficient between the average annual growth rates of TFP and of real wage rates is 0.83.

Our decomposition of average annual growth rates of TFP into autonomous and factor biased technological change by the estimation of translog cost function shed some light on the relative contribution of the factor biased technical change that turns out to be significant in some regions. Let us recall some characteristics of the pulp and paper industry in industrialized countries: it provides a set of fairly homogeneous products, shares a common technology, performs little R&D, and gets its equipment from a small group of manufacturers. This leaves little room for governments to influence technological change targeting production processes. However, this is not necessarily the case for factor biased technical change. Our estimation results show that technical change has been generally capital and material using, and labour saving. The contribution of factor using technical change and decreasing relative price of the relevant factor add a positive contribution to TFP growth. Taxation of capital is a policy tool under government control and it influences the user price of capital goods. Our results draw the attention on one aspect of capital taxation that is often left out in policy analysis. However, it must be kept in mind that it is the rate of change of relative input price that influences TFP change. Thus relative input prices must keep changing to support TFP growth.

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Table 1: Output and Input Quantities: 1971-2005

	AB	BC	ON	QC	GA	IL	ME	WA	FIN	SWE
Output (1992 CAN$ in millions)										
1971	256	3113	5476	5609	5125	5879	3315	4010	4718	8042
2005	1332	4251	8527	8520	8494	5025	3326	4470	17011	16835
(71–05)[a]	4.8	0.9	1.3	1.23	1.4	-0.4	0.01	0.3	3.7	2.1
Labour (man years)										
1971	1562	18327	43867	42125	24788	37988	16856	18048	57448	55387
2005	2957	12123	29681	26995	23716	25477	9177	12175	32700	36096
(71–05)[a]	1.8	-1.2	-1.1	-1.3	-0.1	-1.2	-1.8	-1.2	-1.7	-1.3
Capital (1992 CAN$ in millions)										
1971	175	5045	3079	3537	3639	2117	1521	2864	12134	8134
2005	1158	2465	3252	4571	6171	3590	2580	4856	15917	12995
(71–05)[a]	5.5	-2.1	0.2	0.8	1.5	1.6	1.6	1.6	0.8	1.3
Materials (1992 CAN$ in millions)										
1971	152	1730	3116	3031	3404	3497	2334	2572	1829	5622
2005	781	3023	5836	5869	4714	2669	1834	2717	11021	11568
(71–05)[a]	4.8	1.6	1.8	1.9	0.9	-0.8	-0.7	0.2	5.2	2.1
Electricity (TJ)										
1971	337	13329	15275	33485	3482	6052	1624	9556	31356	25024
2005	9850	33038	26096	76434	10195	10324	1839	8496	83830	70747
(71–05)[a]	9.2	2.7	1.6	2.4	3.2	1.5	0.4	-0.3	2.9	3.1
Other Energy (TJ)										
1971	2587	33953	50434	49494	61534	106012	18238	73025	40802	81945
2005	10574	14975	39722	19938	113828	84799	19272	61605	56799	95659
(71–05)[a]	4.1	-2.4	-0.7	-2.7	1.8	-0.7	0.2	-0.5	0.9	0.5

Notes: *a*. Average annual growth rate (%). Units of electricity and other energies are in terajoule.

Table 2: Input Prices and Cost Shares: 1971-2005

	AB	BC	ON	QC	GA	IL	ME	WA	FIN	SWE
Wage (1992 CAN$ per man year)										
1971	30418	40042	31368	32464	41301	40847	43396	47477	18631	25444
2005	53865	56586	45761	44582	46804	40885	49049	52659	55274	55843
(71–05)[a]	1.6	0.9	1.1	0.9	0.4	0.0	0.4	0.3	3.2	2.3
Rate of Return (%)										
1971	0.40	0.12	0.33	0.28	0.29	0.29	0.26	0.18	0.14	0.10
2005	0.26	0.34	0.52	0.46	0.25	0.14	0.22	0.14	0.22	0.29
(71–05)[a]	-1.2	3.1	1.4	1.4	-0.4	-2.1	-0.6	-0.7	1.3	3.1
Materials (1992=1.00)										
1971	0.86	0.91	0.91	0.97	0.90	0.91	0.90	0.91	0.94	0.75
2005	0.94	0.72	0.81	0.73	0.98	0.96	1.19	0.95	1.01	0.93
(71–05)[a]	0.2	-0.7	-0.3	-0.8	0.2	0.2	0.8	0.1	0.6	3.1
Electricity ($/TJ)										
1971	7443	5916	7847	5053	15177	18260	17481	4805	12266	11095
2005	4937	8302	18186	7269	14107	12322	19445	11400	9878	8987
(71–05)[a]	-1.2	1.0	2.5	1.1	-0.2	-1.1	0.3	2.5	-0.6	-0.6
Other Energy ($/TJ)										
1971	1841	3360	2494	3349	3491	4031	3107	3691	2573	2328
2005	7862	16299	5739	19390	6958	9120	4989	7753	5706	5192
(71–05)[a]	4.3	4.6	2.5	5.2	2.0	2.4	1.4	2.2	2.3	2.4
Input Cost Share (%)										
Capital	0.30	0.24	0.23	0.24	0.17	0.11	0.13	0.12	0.22	0.24
Labour	0.15	0.19	0.19	0.19	0.15	0.20	0.16	0.16	0.15	0.13
Materials	0.50	0.49	0.50	0.47	0.60	0.55	0.66	0.60	0.52	0.55
Electricity	0.02	0.04	0.03	0.04	0.01	0.02	0.01	0.01	0.07	0.04
Other Energy	0.02	0.05	0.02	0.03	0.05	0.09	0.02	0.08	0.02	0.02

Notes: *a*. Average annual growth rate (%). TJ refers to terajoules.

Table 3: Total Factor Productivity Index, 1971–2005

Year	AB	BC	ON	QC	GA	IL	ME	WA	FIN	SWE	σ_{10}	σ_8
1971	0.97	0.82	0.95	0.95	0.95	1.01	1.00	0.93	0.69	0.79	0.10	0.06
1972	0.85	0.84	0.96	0.95	0.99	1.06	1.00	0.98	0.67	0.82	0.12	0.07
1973	0.82	0.85	0.98	0.95	1.02	1.12	1.05	0.99	0.65	0.89	0.13	0.10
1974	0.91	0.86	1.01	0.97	1.03	1.13	1.07	0.99	0.72	0.82	0.12	0.09
1975	0.86	0.83	0.98	0.96	1.01	1.06	1.05	0.98	0.60	0.60	0.17	0.08
1976	0.91	0.87	0.96	0.94	1.06	1.05	1.09	1.01	0.69	0.63	0.15	0.08
1977	0.91	0.87	0.96	0.95	1.03	1.09	1.12	1.01	0.70	0.66	0.15	0.09
1978	0.92	0.88	0.97	0.97	1.05	1.12	1.17	1.00	0.71	0.77	0.14	0.10
1979	0.87	0.89	1.00	0.98	1.07	1.14	1.18	1.03	0.72	0.73	0.16	0.11
1980	0.90	0.89	1.01	0.98	1.07	1.11	1.15	1.01	0.74	0.72	0.15	0.09
1981	0.93	0.87	1.00	0.97	1.06	1.10	1.13	0.98	0.75	0.69	0.14	0.09
1982	1.01	0.88	1.00	0.95	1.07	1.11	1.12	0.97	0.72	0.72	0.14	0.08
1983	1.00	0.88	1.00	0.96	1.06	1.09	1.11	1.02	0.76	0.80	0.12	0.07
1984	1.07	0.87	1.01	0.96	1.13	1.09	1.17	1.03	0.74	0.82	0.14	0.10
1985	1.04	0.90	1.01	0.95	1.07	1.11	1.16	1.00	0.75	0.80	0.13	0.08
1986	0.96	0.91	1.02	0.94	1.13	1.12	1.15	1.05	0.75	0.83	0.13	0.09
1987	0.97	0.94	1.03	0.92	1.12	1.06	1.12	1.07	0.77	0.86	0.12	0.08
1988	0.81	0.93	1.03	0.93	1.17	1.06	1.21	1.12	0.80	0.85	0.15	0.14
1989	0.70	0.88	1.03	0.92	1.16	1.05	1.15	1.07	0.83	0.85	0.15	0.15
1990	0.73	0.85	1.03	0.93	1.10	1.05	1.11	1.01	0.84	0.81	0.13	0.13
1991	0.80	0.87	1.02	0.92	1.09	1.06	1.04	0.98	0.87	0.89	0.10	0.10
1992	0.84	0.88	1.02	0.92	1.13	1.06	1.01	0.94	0.87	0.93	0.09	0.10
1993	0.82	0.90	1.03	0.93	1.13	1.13	1.05	0.99	0.88	1.06	0.11	0.11
1994	0.90	0.88	1.04	0.94	1.13	1.14	1.06	1.00	0.92	1.03	0.09	0.10
1995	0.85	0.87	1.05	0.94	1.09	0.99	1.27	0.96	0.90	0.88	0.13	0.14
1996	0.80	0.91	1.05	0.94	1.08	1.04	1.18	0.93	0.90	0.88	0.11	0.12
1997	0.86	0.91	1.06	0.96	1.12	1.08	1.14	0.99	0.94	0.93	0.10	0.10
1998	0.78	0.91	1.08	0.96	1.10	1.04	1.16	0.94	0.94	0.94	0.11	0.12
1999	0.88	0.93	1.08	0.97	1.12	1.00	1.21	0.92	0.95	1.00	0.10	0.11
2000	1.01	0.96	1.10	0.99	1.09	0.92	1.15	0.92	0.96	1.01	0.08	0.09
2001	0.88	0.95	1.11	1.00	1.07	0.93	1.12	0.89	0.94	0.98	0.09	0.10
2002	0.95	0.96	1.13	1.03	1.10	0.96	1.13	0.90	0.98	1.01	0.08	0.09
2003	1.04	0.99	1.12	1.01	1.10	0.96	1.13	0.97	1.02	1.07	0.06	0.07
2004	1.04	1.02	1.12	1.02	1.13	0.99	1.14	0.97	1.06	1.05	0.06	0.07
2005	1.04	1.03	1.13	1.06	1.12	1.00	1.18	0.98	1.03	1.02	0.06	0.07
(71–05)[a]	0.19	0.67	0.49	0.31	0.48	-0.04	0.49	0.17	1.18	0.76	–	–

Notes: *a*. Average annual growth rate (%). σ_{10} refers to the standard deviation of TFP levels across the ten regions. σ_8 refers to the standard deviation of TFP levels across the eight U.S. and Canadian regions.

Table 4: Coverage of Concavity by the Estimated Translog Cost Function

	Concavity Coverage when Not Imposed		Concavity Coverage when Imposed		
Region	Number of Data Points	At the Mean of Data	Number of Data Points	At the Mean of Data	Point of Imposition*
Alberta	5 (14%)	No	27 (77%)	Yes	17
British Columbia	8 (23%)	No	29 (83%)	Yes	5
Ontario	11 (31%)	Yes	27 (77%)	Yes	4
Québec	9 (26%)	No	28 (80%)	Yes	13
Georgia	7 (20%)	No	33 (94%)	Yes	19
Illinois	0 (0%)	No	29 (83%)	Yes	3
Maine	1 (3%)	No	25 (71%)	Yes	1
Washington	9 (26%)	Yes	17 (49%)	Yes	1
Finland	2 (6%)	No	25 (71%)	Yes	31
Sweden	14 (40%)	Yes	30 (86%)	Yes	25

Note: * Highest number of data points satisfies concavity when concavity is imposed at this data point.

Table 5: Test Statistics for Likelihood Ratio Tests

Region	No Technical Change	Neutral Technical Change	Pooling
Alberta	121.84	111.56	1089.40*
British Columbia	96.20	44.02	
Ontario	154.45	107.55	
Québec	131.72	80.69	
Georgia	138.82	132.45	1415.17**
Illinois	108.59	70.88	
Maine	67.90	58.50	
Washington	54.20	44.28	
Finland	145.14	84.59	—
Sweden	93.46	56.49	—

Notes: Test for no technical change in the TL model requires 6 parameter restrictions. Test for neutral technical change in the TL model involves 4 restrictions. * Test statistic for poolability of data for Canadian Provinces. ** Test statistic for poolability of data for US states. In all cases, $prob > \chi^2 = 0.0000$.

Table 6: Translog Parameter Estimates for Canadian Provinces

Parameter	Alberta	British Columbia	Ontario	Québec
α_K	.3872 (.0274)	.1810 (.0093)	.2628 (.0086)	.1836 (.0049)
α_L	.1336 (.0042)	.2424 (.0044)	.2047 (.0022)	.2229 (.0027)
α_F	.0179 (.0017)	.0409 (.0022)	.0214 (.0013)	.0646 (.0022)
α_E	.0141 (.0013)	.0232 (.0018)	.0161 (.0008)	.0518 (.0029)
α_{KK}	.1451 (.0147)	.1230 (.0066)	.1066 (.0104)	.1318 (.0055)
α_{LL}	.0867 (.0113)	.0643 (.0156)	.0770 (.0065)	.0903 (.0116)
α_{FF}	.0135 (.0015)	.0213 (.0029)	.0197 (.0012)	.0330 (.0034)
α_{EE}	.0135 (.0015)	.0213 (.0029)	.0197 (.0012)	.0330 (.0034)
α_{KL}	.0135 (.0015)	.0213 (.0029)	.0197 (.0012)	.0330 (.0034)
α_{KF}	-.0109 (.0016)	-.0094 (.0020)	-.0084 (.0012)	-.0141 (.0028)
α_{KE}	-.0139 (.0016)	-.0116 (.0016)	-.0097 (.0028)	-.0121 (.0028)
α_{LF}	-.0112 (.0024)	-.0056 (.0008)	-.0028 (.0018)	.0067 (.0036)
α_{LE}	-.0097 (.0045)	.0077 (.0020)	.0099 (.0030)	-.0270 (.0074)
α_{FE}	-.0043 (.0013)	.0080 (.0020)	-.0019 (.0004)	-.0004 (.0004)
α_{Kt}	.0023 (.0010)	-.0011 (.0005)	.0020 (.0004)	.0026 (.0004)
α_{Lt}	-.0034 (.0003)	-.0023 (.0003)	-.0030 (.0001)	-.0031 (.0002)
α_{Ft}	.0003 (.0001)	-.0003 (.0001)	-.0002 (.0001)	-.0010 (.0001)
α_{Et}	.0017 (.0001)	.0007 (.0001)	.0006 (.0000)	.0008 (.0002)
α_t	-.0015 (.0025)	-.0090 (.0016)	-.0018 (.0007)	-.0031 (.0005)
α_{tt}	.0009 (.0002)	.0004 (.0001)	-.0001 (.0000)	-.0001 (.0001)
Constant	.0779 (.0274)	-1.3494 (.0118)	-.9168 (.0086)	-.2166 (.0051)
R^2 *values*				
Cost Eq.	0.78	0.90	0.97	0.93
Capital Eq.	0.20	0.74	0.61	0.73
Labour Eq.	0.54	0.87	0.98	0.96
Other Energy Eq.	0.58	0.69	0.90	0.58
Electricity Eq.	0.90	0.87	0.98	0.82

Note: Standard errors of the parameter estimates are reported in parenthesis.

Table 7: Translog Parameter Estimates for U.S. States, Finland, and Sweden

	US					
Parameter	Georgia	Illinois	Maine	Washington	Finland	Sweden
α_K	.1913 (.0060)	.1349 (.0039)	.0936 (.0084)	.1154 (.0057)	.2669 (.0067)	.3194 (.0026)
α_L	.1315 (.0041)	.2387 (.0068)	.2154 (.0035)	.2034 (.0037)	.1077 (.0066)	.1039 (.0026)
α_F	.0420 (.0008)	.0752 (.0024)	.0182 (.0016)	.0872 (.0033)	.0156 (.0014)	.0162 (.0009)
α_E	.0145 (.0003)	.0211 (.0006)	.0088 (.0004)	.0179 (.0011)	.0503 (.0026)	.0380 (.0018)
α_{KK}	.0248 (.0042)	.0459 (.0050)	.0264 (.0094)	.0555 (.0062)	.1235 (.0060)	.1516 (.0030)
α_{LL}	.0903 (.0180)	.1132 (.0290)	.1475 (.0150)	.1284 (.0210)	.0774 (.0130)	.0541 (.0100)
α_{FF}	.0383 (.0040)	.0664 (.0030)	.0164 (.0016)	.0651 (.0046)	.0152 (.0016)	.0152 (.0010)
α_{EE}	.0140 (.0010)	.0207 (.0012)	.0086 (.0012)	.0142 (.0011)	.0477 (.0024)	.0175 (.0040)
α_{KL}	-.0352 (.0078)	-.0600 (.0080)	-.0494 (.0070)	-.0403 (.0044)	-.0240 (.0050)	-.0389 (.0030)
α_{KF}	-.0240 (.0040)	-.0244 (.0034)	-.0051 (.0015)	-.0312 (.0039)	-.0044 (.0017)	-.0038 (.0010)
α_{KE}	-.0037 (.0010)	-.0021 (.0009)	-.0017 (.0008)	-.0040 (.0012)	-.0115 (.0028)	-.0144 (.0020)
α_{LF}	-.0075 (.0060)	-.0273 (.0065)	-.0027 (.0020)	-.0217 (.0040)	-.0002 (.0000)	-.0033 (.0006)
α_{LE}	.0009 (.0018)	-.0033 (.0027)	-.0017 (.0020)	-.0089 (.0030)	-.0065 (.0008)	-.0244 (.0050)
α_{FE}	-.0006 (.0008)	-.0013 (.0009)	-.0005 (.0002)	-.0051 (.0012)	-.0007 (.0002)	.0009 (.0002)
α_{Kt}	.0029 (.0003)	.0010 (.0003)	.0020 (.0004)	.0015 (.0003)	-.0028 (.0004)	.0002 (.0001)
α_{Lt}	-.0007 (.0002)	-.0029 (.0005)	-.0023 (.0002)	-.0019 (.0002)	-.0054 (.0006)	-.0030 (.0002)
α_{Ft}	.0005 (.0001)	-.0012 (.0003)	.0001 (.0001)	-.0012 (.0002)	-.0004 (.0001)	-.0002 (.0000)
α_{Et}	.0003 (.0000)	.0003 (.0000)	.0001 (.0000)	-.0002 (.0001)	.0003 (.0002)	.0006 (.0001)
α_t	-.0013 (.0004)	-.0088 (.0012)	-.0138 (.0017)	-.0103 (.0016)	-.0238 (.0012)	-.0135 (.0025)
α_{tt}	.0007 (.0001)	.0008 (.0001)	-.0006 (.0001)	.0007 (.0001)	-.0006 (.0001)	-.0004 (.0001)
Constant	-.0325 (.0047)	-1.2044 (.0108)	-1.3256 (.0167)	-1.3683 (.0157)	.2683 (.0131)	.4101 (.0194)
R^2 values						
Cost Eq.	0.76	0.60	0.70	0.35	0.84	0.73
Capital Eq.	0.80	0.64	0.49	0.72	0.76	0.98
Labour Eq.	0.55	0.63	0.84	0.72	0.77	0.90
Other Energy Eq.	0.90	0.76	0.77	0.80	0.80	0.87
Electricity Eq.	0.86	0.76	0.75	0.73	0.77	0.74

Note: Standard errors of the parameter estimates are reported in parenthesis.

Table 8: Point Estimates and Confidence Intervals for Input Price Elasticities in Canadian Provinces

Factor i	Region	Price Elasticities				
		η_{Ki}	η_{Li}	η_{Mi}	η_{Ei}	η_{Fi}
(K)	Alberta	-0.21	0.04	0.21	-0.02	-0.01
		(-0.37, -0.16)	(0.02, 0.08)	(0.17, 0.34)	(-0.04, -0.02)	(-0.02, 0.00)
	BC	-0.23	-0.01	0.24	-0.01	0.01
		(-0.29, -0.19)	(-0.04, 0.03)	(0.19, 0.30)	(-0.02, 0.01)	(-0.01, 0.02)
	Ontario	-0.3	-0.02	0.34	-0.01	-0.01
		(-0.29, -0.19)	(-0.04, 0.03)	(0.19, 0.30)	(-0.02, 0.01)	(-0.01, 0.02)
	Québec	-0.2	-0.04	0.26	0.00	-0.02
		(-0.24, -0.17)	(-0.07, -0.01)	(0.21, 0.32)	(-0.02, 0.02)	(-0.04, 0.00)
(L)	Alberta	0.07	-0.28	0.29	-0.04	-0.05
		(0.03, 0.14)	(-0.42, -0.10)	(0.07, 0.44)	(-0.10, 0.02)	(-0.08, -0.01)
	BC	-0.01	-0.47	0.38	0.08	0.02
		(-0.05, 0.03)	(-0.65, -0.32)	(0.26, 0.53)	(0.03, 0.14)	(-0.03, 0.07)
	Ontario	-0.02	-0.41	0.34	0.08	0.01
		(-0.05, 0.01)	(-0.48, -0.34)	(0.29, 0.38)	(0.05, 0.12)	(-0.00, 0.03)
	Québec	-0.05	-0.34	0.40	-0.03	0.07
		(-0.08, -0.01)	(-0.48, -0.23)	(0.31, 0.52)	(-0.16, -0.00)	(0.03, 0.11)
(M)	Alberta	0.12	0.09	-0.32	0.06	0.05
		(0.10, 0.20)	(0.02, 0.13)	(-0.42, -0.26)	(0.05, 0.10)	(0.04, 0.06)
	BC	0.11	0.14	-0.28	0.01	0.02
		(0.09, 0.13)	(0.10, 0.20)	(-0.34, -0.23)	(-0.01, 0.02)	(0.01, 0.04)
	Ontario	0.14	0.13	-0.3	0.01	0.01
		(0.11, 0.18)	(0.11, 0.15)	(-0.34, -0.26)	(0.01, 0.02)	(0.007, 0.02)
	Québec	0.13	0.16	-0.33	0.05	-0.01
		(0.10, 0.15)	(0.13, 0.21)	(-0.40, -0.28)	(0.03, 0.09)	(-0.03, 0.01)
(E)	Alberta	-0.25	-0.22	0.47	-0.61	-0.14
		(-0.43, -0.17)	(-0.55, 0.13)	(0.38, 0.91)	(-1.04, -0.58)	(-0.19, 0.02)
	BC	-0.06	0.37	0.08	-0.64	0.24
		(-0.12, 0.03)	(0.13, 0.63)	(-0.09, 0.27)	(-0.77, -0.55)	(0.17, 0.31)
	Ontario	-0.06	0.49	0.21	-0.6	-0.03
		(-0.11, -0.01)	(0.31, 0.69)	(0.11, 0.31)	(-0.82, -0.52)	(-0.07, 0.06)
	Québec	-0.01	-0.34	0.51	-0.19	0.04
		(-0.12, 0.10)	(-0.62, -0.01)	(0.29, 0.95)	(-0.78, -0.08)	(-0.07, 0.22)
(F)	Alberta	-0.14	-0.29	0.94	-0.14	-0.45
		(-0.23, 0.02)	(-0.48, -0.08)	(0.73, 1.21)	(-0.20, 0.02)	(-0.61, -0.36)
	BC	0.04	0.07	0.21	0.20	-0.52
		(-0.03, 0.11)	(-0.11, 0.25)	(0.05, 0.41)	(0.14, 0.26)	(-0.61, -0.45)
	Ontario	-0.09	0.10	0.28	-0.04	-0.24
		(-0.19, 0.01)	(-0.04, 0.24)	(0.14, 0.43)	(-0.08, 0.08)	(-0.41, -0.19)
	Québec	-0.13	0.37	-0.18	0.05	-0.11
		(-0.24, 0.02)	(0.17, 0.54)	(-0.42, 0.08)	(-0.10, 0.26)	(-0.33, -0.08)

Note: Elasticities are calculated at the mean of the data, and 95% confidence intervals for the estimates are reported in parenthesis.

Table 9: Point Estimates and Confidence Intervals for Input Price Elasticities in U.S. States

Factor i	Region	Price Elasticities η_{Ki}	η_{Li}	η_{Mi}	η_{Ei}	η_{Fi}
(K)	Georgia	-0.68	-0.05	0.83	-0.01	-0.08
		(-0.97, -0.37)	(-0.18, -0.01)	(0.69, 1.06)	(-0.08, 0.05)	(-0.18, 0.05)
	Illinois	-0.50	-0.29	0.88	0.01	-0.11
		(-0.59, -0.40)	(-0.43, -0.15)	(0.74, 1.16)	(-0.02, 0.01)	(-0.21, -0.10)
	Maine	-0.67	-0.17	0.80	0.00	0.00
		(-0.52, 0.78)	(-0.34, -0.11)	(0.72, 1.12)	(-0.04, 0.04)	(-0.06, 0.02)
	Washington	-0.43	-0.16	0.36	-0.01	0.00
		(-0.54, -0.34)	(-0.23, -0.08)	(0.24, 0.68)	(-0.04, 0.02)	(-0.18, 0.03)
(L)	Georgia	-0.06	-0.25	0.29	0.02	-0.01
		(-0.19, -0.01)	(-0.49, -0.11)	(0.25, 0.57)	(-0.01, 0.08)	(-0.11, 0.04)
	Illinois	-0.16	-0.25	0.44	0.01	-0.03
		(-0.24, -0.09)	(-0.62, -0.07)	(0.26, 0.63)	(-0.04, 0.03)	(-0.16, -0.02)
	Maine	-0.13	-0.11	0.23	0.00	0.01
		(-0.19, -0.02)	(-0.22, 0.06)	(0.18, 0.32)	(-0.06, 0.04)	(-0.06, 0.08)
	Washington	-0.06	-0.12	0.22	-0.04	0.01
		(-0.17, -0.06)	(-0.41, -0.09)	(0.20, 0.57)	(-0.08, 0.09)	(-0.02, 0.13)
(M)	Georgia	0.24	0.07	-0.35	0.00	0.05
		(0.18, 0.37)	(0.02, 0.16)	(-0.57, -0.18)	(-0.11, 0.10)	(0.03, 0.24)
	Illinois	0.19	0.17	-0.44	0.00	0.07
		(0.16, 0.25)	(0.10, 0.36)	(-0.74, -0.39)	(-0.00, 0.09)	(0.06, 0.21)
	Maine	0.16	0.06	-0.22	0.00	0.01
		(0.02, 0.23)	(0.01, 0.08)	(-0.36, -0.14)	(-0.17, 0.05)	(-0.04, 0.12)
	Washington	0.07	0.06	-0.33	0.04	0.06
		(0.04, 0.9)	(0.01, 0.12)	(-0.41, -0.17)	(0.02, 0.10)	(0.03, 0.14)
(E)	Georgia	-0.07	0.21	0.05	-0.25	0.01
		(-0.13, 0.01)	(0.17, 0.59)	(0.02, 0.12)	(-0.39, -0.15)	(-0.12, 0.09)
	Illinois	0.04	0.09	0.03	-0.21	0.05
		(-0.14, 0.06)	(-0.34, 0.25)	(-0.04, 0.50)	(-0.60, -0.13)	(-0.34, 0.20)
	Maine	-0.03	0.02	0.27	-0.25	-0.02
		(-0.10, 0.12)	(-0.23, 0.17)	(0.18, 0.42)	(-0.30, -0.08)	(-0.16, 0.12)
	Washington	-0.06	-0.31	0.68	-0.31	-0.17
		(-0.08, 0.04)	(-0.47, 0.04)	(0.44, 0.76)	(-0.59, -0.08)	(-0.30, -0.09)
(F)	Georgia	-0.26	-0.02	0.50	0.00	-0.25
		(-0.39, -0.12)	(-0.21, 0.05)	(0.41, 0.67)	(-0.05, 0.18)	(-0.42, -0.09)
	Illinois	-0.13	-0.07	0.41	0.01	-0.22
		(-0.30, -0.13)	(-0.38, -0.04)	(0.38, 0.90)	(-0.36, 0.06)	(-0.62, -0.13)
	Maine	-0.02	0.05	0.30	-0.01	-0.29
		(-0.26, 0.08)	(0.00 0.06)	(0.14, 0.48)	(0.04, 0.06)	(-0.62, -0.20)
	Washington	0.00	0.01	0.52	-0.04	-0.32
		(-0.15, 0.02)	(-0.04, 0.08)	(0.38, 0.71)	(-0.08, 0.02)	(-0.35, -0.11)

Note: Elasticities are calculated at the mean of the data, and 95% confidence intervals for the estimates are reported in parenthesis.

Table 10: Point Estimates and Confidence Intervals for Input Price Elasticities in Finland and Sweden

Factor i	Region	Price Elasticities				
		η_{Ki}	η_{Li}	η_{Mi}	η_{Ei}	η_{Fi}
(K)	Finland	-0.22	0.05	0.14	0.02	0.01
		(-0.29, -0.16)	(-0.00, 0.11)	(0.06, 0.47)	(-0.01, 0.08)	(-0.07, 0.06)
	Sweden	-0.13	-0.03	0.16	-0.01	0.01
		(-0.16, -0.10)	(-0.05, -0.00)	(0.11, 0.21)	(-0.03, 0.01)	(0.00, 0.02)
(L)	Finland	0.08	-0.36	0.23	0.03	0.02
		(-0.00, 0.15)	(-0.61, -0.26)	(0.17, 0.35)	(-0.04, 0.13)	(-0.04, 0.09)
	Sweden	-0.05	-0.46	0.64	-0.14	0.00
		(-0.09, -0.00)	(-0.63, -0.33)	(0.47, 0.84)	(-0.21, -0.05)	(-0.04, 0.05)
(M)	Finland	0.06	0.07	-0.16	0.02	0.00
		(0.01, 0.11)	(0.01, 0.19)	(-0.47, -0.11)	(-0.16, 0.10)	(-0.08, 0.15)
	Sweden	0.07	0.16	-0.32	0.08	0.01
		(0.04, 0.09)	(0.11, 0.21)	(-0.39, -0.25)	(0.06, 0.11)	(-0.00, 0.02)
(E)	Finland	0.07	0.07	0.12	-0.28	0.01
		(0.01, 0.14)	(0.01, 0.21)	(0.03, 0.19)	(-0.41, -0.13)	(-0.15, 0.18)
	Sweden	-0.07	-0.39	0.79	-0.58	0.05
		(-0.17, 0.02)	(-0.63, -0.17)	(0.72, 1.41)	(-0.90, -0.44)	(-0.03, 0.16)
(F)	Finland	0.05	0.16	0.26	0.04	-0.43
		(-0.01, 0.10)	(-0.01, 0.21)	(0.20, 0.57)	(-0.01, 0.12)	(-0.69, -0.31)
	Sweden	0.11	0.02	0.23	0.08	-0.43
		(0.00, 0.20)	(-0.20, 0.21)	(-0.05, 0.55)	(-0.06, 0.27)	(-0.57, -0.39)

Note: Elasticities are calculated at the mean of the data, and 95% confidence intervals for the estimates are reported in parenthesis.

Table 11: Factor Biases of Technical Change in the Pulp and Paper Industry

Region	Capital	Labour	Materials	Other Energy	Electricity
Alberta	0.0023	-0.0034	-0.0009	0.0003	0.0017
British Columbia	-0.0011	-0.0023	0.0030	-0.0003	0.0007
Ontario	0.0020	-0.0030	0.0006	-0.0002	0.0006
Québec	0.0026	-0.0031	0.0007	-0.0010	0.0008
Georgia	0.0029	-0.0007	-0.0030	0.0005	0.0003
Illinois	0.0010	-0.0029	0.0028	-0.0012	0.0003
Maine	0.0020	-0.0023	0.0001	0.0001	0.0001
Washington	0.0015	-0.0019	0.0018	-0.0012	-0.0002
Finland	-0.0028	-0.0054	0.0083	-0.0004	0.0003
Sweden	0.0002	-0.0030	0.0024	-0.0002	0.0006

Table 12: Average Annual Growth Rates of TFP in the Pulp and Paper Industry

Region	Autonomous Technical Change (%)	Biased Technical Change (%)	Growth Rates of Productivity
Alberta	0.06	0.14	0.20
British Columbia	0.44	0.02	0.46
Ontario	0.31	0.12	0.43
Québec	0.33	-0.10	0.23
Georgia	0.20	0.09	0.29
Illinois	-0.34	0.06	-0.28
Maine	0.39	-0.02	0.37
Washington	-0.16	0.06	-0.10
Finland	1.62	-0.42	1.20
Sweden	1.08	0.00	1.08

Table 13: Results for Convergence and Panel Data Unit Root Test

Variable	Coefficient	Standard Error	Unit Root Test Statistics*
$\ln TFP$	-0.1657	0.0304	-2.6801
$\left(\widehat{\frac{K}{L}}\right)$	-0.1605	0.0220	-4.0294
$\left(\widehat{\frac{M}{L}}\right)$	0.1324	0.0261	-3.9738
$\left(\widehat{\frac{E}{L}}\right)$	0.0037	0.0010	-4.3852
$\left(\widehat{\frac{F}{L}}\right)$	-0.0109	0.0194	-3.6082
$\widehat{TFP}$	—	—	-4.0030
Province/State Fixed Effects		Yes	
Time Fixed Effects		Yes	

Note: * Variable $\ln TFP$ included a time trend in the unit root test. The asymptotic standard normal 5% critical value is -1.65.

Appendix A Data Framework

Total revenue can be decomposed into factor payments:

$$P_tQ_t = P_{lt}L_t + P_{kt}K_t + P_{mt}M_t + P_{ft}F_t + P_{et}E_t \tag{A.1}$$

where,

Q_t = total shipments in constant dollars;

L_t = number of workers;

K_t = value of net capital stock in constant dollars;

M_t = value of materials in constant dollars;

F_t = quantity of purchased fossil fuels (coal, petroleum products, and natural gas) in Terajoules (TJ);

E_t = purchased electricity in TJ;

P_t = industry selling price index;

P_{lt} = average annual wage in current dollars;

P_{kt} = gross rate of return to capital in current dollars;

P_{mt} = material price index;

P_{ft} = unit price of fossil fuels, current dollars per TJ;

P_{et} = unit price of purchased electricity, current dollars per TJ.

Note that:

P_tQ_t = total value of shipments (TVS_t) in current dollars;

$P_{lt}L_t + P_{kt}K_t$ = value added (VA_t) in current dollars.

Data on P_t, P_{lt}, L_t, K_t, P_{ft}, F_t, P_{et}, E_t, and also on TVS_t, and VA_t are either directly obtained or constructed from publicly available information. Transformations yield the following variables:

$$Q_t = TVS_t/P_t \tag{A.2}$$

$$P_{kt} = (VA_t - P_{lt}L_t)/K_t \tag{A.3}$$

$$P_{mt}M_t = TVS_t - VA_t - P_{ft}F_t - P_{et}E_t \tag{A.4}$$

The same development can be performed in constant dollars. Then the equivalent to expression (A.4) yields the value of materials in constant dollars, which is identified as the quantity of materials. The ratio of value of materials in current dollars to its value in constant dollars yields P_{mt}, *i.e.*, the materials price index. Constant dollar values are expressed in 1992 Canadian dollars using the exchange rate of this mid-smaple year.

Data for the Canadian provinces come from Statistics Canada while the U.S. data are obtained from the following sources: Annual Survey of Manufactures (Census Bureau), Bureau of Economic Analysis (BEA), State Energy Data System (SEDS) of Energy Information Administration (EIA), and Bureau of Labor Statistics (BLS). Data for Finland come from Statistics Finalnd's PX-Web Databases and the World Energy Balances database of OECD while data for Sweden are obtained by special request to Statistics Sweden and also from Swedish Statistical Yearbook of Forestry 2008, chapters 10-14, published by the Swedish Forest Agency.

Appendix B Imposing Local Concavity

Ryan and Wales (2000) propose a method to impose concavity on the translog cost function locally, at a chosen reference point, since imposing global concavity destroys its flexibility property. Although their method of imposing concavity on a single data point resulted in global concavity coverage for their dataset, this procedure does not guarantee concavity for all data points in the sample. They expect that a judicious choice of point of imposition may lead to concavity coverage at most or all data points.

To impose local concavity on the cost function we rewrite our unit cost function as:

$$\ln\left(\frac{c}{p_M}\right) = \alpha_0 + \sum_i \alpha_i \ln\left(\frac{p_i}{p_M}\right) + \frac{1}{2}\sum_i \sum_j \alpha_{ij} \ln\left(\frac{p_i}{p_M}\right) \ln\left(\frac{p_j}{p_M}\right) + \sum_i \alpha_{it}\left(t-t^*\right) \ln\left(\frac{p_i}{p_M}\right) + \alpha_t\left(t-t^*\right) + \frac{1}{2}\alpha_{tt}\left(t-t^*\right)^2 \tag{B.1}$$

where, t^* is the chosen reference point — the point of imposition of local concavity, and $i, j = K, L, E, F$. The corresponding input share equations are:

$$S_i = \alpha_i + \alpha_{ii} \ln\left(\frac{p_i}{p_M}\right) + \sum_{j \neq i} \alpha_{ij} \ln\left(\frac{p_j}{p_M}\right) + \alpha_{it}\left(t-t^*\right). \tag{B.2}$$

All input prices are normalized to one at t^*. Normalizing all input prices to one at t^* makes $S_i = \alpha_i$, for all i at this data point. So the Hessian of the cost function (B.1) will be negative semi-definite if and only if the matrix $\mathbf{H}$ in (8) is negative definite. The ij^{th} element of $\mathbf{H}$, evaluated at t^*, is defined as:

$$H_{ij} = \alpha_{ij} - \alpha_i \delta_{ij} + \alpha_i \alpha_j \tag{B.3}$$

where, $\delta_{ij} = 1$ if $i = j$ and 0 otherwise. Imposing curvature at the reference point, t^*, is done by setting $\mathbf{H} = -(DD')$, where D is a lower triangular matrix with elements

d_{ij} for $i \geq j$ and 0 elsewhere,

$$D = [d_{ij}] \quad \text{with } d_{ij} = 0 \text{ for } i < j. \tag{B.4}$$

Substituting this in (B.3) and solving for $\mathbf{A}$ gives us:

$$\alpha_{ij} = -\left(DD^{'}\right)_{ij} + \alpha_i \delta_{ij} - \alpha_i \alpha_j \tag{B.5}$$

where $\left(DD^{'}\right)_{ij}$ is the ij^{th} element of $DD^{'}$. This gives us the following relationship between the parameters α_{ij} and d_{ij},

$$\alpha_{KK} = -\,d_{KK}^2 + \alpha_K - \alpha_{KK}^2 \qquad \alpha_{EE} = -\,d_{KE}^2 - d_{LE}^2 - d_{FE}^2 - d_{EE}^2 + \alpha_E - \alpha_E^2$$

$$\alpha_{LL} = -\,d_{KL}^2 - d_{LL}^2 + \alpha_L - \alpha_{LL}^2 \qquad \alpha_{FF} = -\,d_{KF}^2 - d_{LF}^2 - d_{FF}^2 + \alpha_F - \alpha_F^2$$

$$\alpha_{KE} = -\,d_{KK}d_{KE} - \alpha_K\alpha_E \qquad \alpha_{LE} = -\,d_{KL}d_{KE} - d_{LL}d_{LE} - \alpha_L\alpha_E$$

$$\alpha_{KF} = -\,d_{KK}d_{KF} - \alpha_K\alpha_F \qquad \alpha_{FE} = -\,d_{KE}d_{KF} - d_{LE}d_{LF} - d_{FF}d_{FE} - \alpha_E\alpha_F$$

$$\alpha_{KL} = -\,d_{KK}d_{KL} - \alpha_K\alpha_L \qquad \alpha_{LF} = -\,d_{KL}d_{KF} - d_{LL}d_{LF} - \alpha_L\alpha_F$$

Replacing $\mathbf{A} = [\alpha_{ij}]$ in the system of equations (B.1) and (B.2) by the above relationships and estimating d_{ij} will ensure that $\mathbf{H}$, and as a result the estimated translog will be concave at the normalization point, t^*. Nonlinear iterative SUR technique is employed to estimate the system of equations since this replacement makes the system of equations nonlinear in parameters, d_{ij}. As the choice of reference point is arbitrary, if imposition of local concavity at all reference points fails to provide global concavity coverage for the sample, then we choose data point that provides the maximum number of concavity coverage as the ideal reference point.