# Investment in Pollution Abatement and Productivity Change in Canadian Regional Pulp and Paper Industries

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**Abstract**

The performance of pulp and paper industries in four Canadian regions is compared based on the estimation of an input distance function both with and without pollutant outputs. The environmentally sensitive approach provides higher productivity growth estimates for all regions, indicating the need for adjusting conventional measures that ignore the non-marketed benefits of pollution abatement activities. The results also consistently indicate the presence of substantial differences in the regional levels of technical efficiency.

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**Key Words:** productivity; technical change; efficiency; input distance functions; pulp and paper; undesirable outputs; BOD; TSS; pollution abatement

**Abbreviations:** BOD - Biological Oxygen Demand; CPPA - Canadian Pulp and Paper Association; TC - Technical Change; TE - Technical Efficiency; TSS- Total Suspended Solids

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## 1. INTRODUCTION

Pulp and paper is the most significant Canadian manufacturing industry in terms of both economic contributions and industrial impact on the nation's water quality. It is the largest source of direct manufacturing employment for over 66,000 people. Quebec, Ontario, and British Colombia account for 38, 24, and 23 percent, respectively, of the industry's employment.[1] The Atlantic and Prairies provinces collectively account for 18 percent of the employment in the industry. The 162 mills that comprised the industry in 1994 were located in Quebec (67), Ontario (34), British Colombia (28), and Atlantic and Prairie Provinces (33). In the period from 1990 to 1998, pulp and paper was the industry that contributed the most to Canada's merchandise trade balance, $137.9 billion, higher than the contribution by energy ($120.4 billion), logging and wood industries ($92.4 billion), mining ($82.9 billion), the auto, trucks and parts industry ($74.2 billion) or fisheries ($16.2).[2] This industry is the world's largest market pulp supplier, accounting for more than 28.1 percent of world supply of market pulp in 1997. Canada is also the largest producer and exporter of newsprint in the world; more than 25 percent of the world's newspaper printing uses Canadian paper.

Growth in the industry over the last three decades was fastest in the province of British Columbia. In the period from 1970 to 1993 the net output of pulp and paper from British Columbia expanded at an average annual rate of 4.76%, tripling the size of the industry in that province. In the Atlantic and Prairies regions, the rate of net output expansion occurred at an average of 1.05% per year, while in Quebec the industry expanded at the rate of 0.46%. Growth was slowest in Ontario, where the industry output had expanded at the rate of only 0.06%.

[1] These figures are from "Principal Statistics" data obtained from Statistics Canada by special request.
[2] The total merchandise trade balance was $172.3 billion for 1990-98. These figures are calculated from the *Reference Tables* published by the Canadian Pulp and Paper Association (CPPA).

The industry has received considerable attention from the public as well as from provincial and federal governments because of its environmental effects. Not only does the industry consume vast amounts of forest resources for its production of pulp and paper, but it also produces significant amounts of water and, to a lesser extent, air and land pollution. Estimates indicate that the pulp and paper industry's contribution to national air emissions range from lows of 0.84 percent for CO and 1.9 percent for VOC (volatile organic compounds) to a high of 7.7 percent for particulate matter, with $NO_x$ and $SO_2$ in between at 2.5 percent and 3.8 percent of the total man-made sources (Environment Canada 1995). However, the Canadian pulp and paper industry is the most important source of water pollution in Canada. Thus, most of the attention on the Canadian pulp and paper industry has focused on its water pollution output.

The pulping, bleaching and paper making processes generate a large volume of water effluents containing pollutants, mainly wood particles, organic material and waste chemicals from the pulping and bleaching process. The wood particles are measured as *total suspended solids* (TSS) and are expressed in kilograms. Suspended solids increase turbidity, upset aquatic habitat and ruin fish spawning beds. Organic matter contained in mill effluents stimulates algal growth and consumes dissolved oxygen, thereby reducing the ability of the water to support aquatic life. This oxygen consumption potential of dissolved organic material is generally measured as *biological oxygen demand* (BOD) expressed in kilograms per tonne of product. Mill effluents also carry toxic substances such as resins, fatty acids, and, in the case of mills that use elemental chlorine for bleaching, a very large number of organochlorine compounds.[3]

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[3] Dioxins and furans have also been identified in emissions from chlorine bleaching and from burning of black liquor during the recovery of chemicals used in the sulphate pulping process. The pulp and paper industry has spent large sums of money to reduce or eliminate discharge of dioxins and furans in response to publicity and public fear of dioxins which peaked with the discovery of dioxins in milk cartons (Murray 1992). Between 1988 and 1993,

The pulp and paper industry has been facing additional constraints that regulate the release of various pollutants. Total suspended solids, biological oxygen demand and, more recently, dioxins and furans are among the indicators selected by regulatory authorities in Canada for the purpose of monitoring pulp and paper industry pollution. Unlike the 1971 regulations, the Fisheries Act regulations introduced in 1992 apply to all mills and are not restricted to new mills or to mills that undergo significant expansion. These regulations apply to discharges of BOD, TSS, and effluents acutely lethal to fish.[4]

The industry has spent large sums of money for pollution abatement purposes over the last three decades. In Quebec, the average annual capital expenditures for water pollution abatement increased from 11.62 million dollars during the 1970s to 129.60 million dollars for the period from 1990 to 1994. The corresponding increases in other regions were: from 14.95 to 51.30 million in Ontario; from 13.06 to 53.36 in the Atlantic and Prairie provinces; and from 16.50 to 228.36 million in British Columbia.

As a result, the rates of water pollutant outputs have been reduced dramatically in the period after 1970. For example, the ratio of BOD output to woodpulp production has been reduced by over 67% in all regions in the period after 1970. The rates of TSS output had also been reduced by at least 80% in all the regions. As a result the absolute levels of BOD and TSS outputs had been reduced by more than 67% and 70%, respectively, in all the regions, despite the continuous expansion in the size of the pulp and paper industry that has occurred over the same period. See Table I for a summary of the changes in marketed and pollutant output rates.

The dramatic changes in the environmental effects of the pulp and paper industry are not

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discharge of dioxins and furans fell by 98 percent (OECD 1995).

[4] These regulations can simplistically be summarized as maximum monthly average rates on BOD and TSS of 7.5 and 11.3 kg per tonne of product, respectively. See Department of Fisheries and Oceans (1992).

taken into account in previous studies that have attempted to assess the productivity performance of the industry. Conventional approaches to productivity measurement count in marketed outputs and marketed inputs only to the neglect of changes in undesirable outputs that are jointly produced in the manufacturing of pulp and paper. This amounts to a partial accounting of the utilization of scarce input resources in the industry: the cost of pollution abatement is included in the input costs while the benefits of pollution abatement (e.g. reduction in water pollution) are ignored. In an industry that has been investing heavily in pollution abatement, the conventional approach is likely to understate the true productivity growth in the industry. Failure to take the pollution abatement activities of the industry into account, may, at least in part, explain the very low or negative productivity growth rate estimates that have been obtained by several previous studies on the industry. See Martinello (1985), Frank *et al* (1990) or Hsue and Buongiorno (1994), for example. A more appropriate approach to productivity analysis requires the use of models that provide a more appropriate representation of the technology by including both desirable and undesirable outputs.

This paper presents the results from an environmentally sensitive input distance function analysis of the regional pulp and paper industries in Canada. The traditional water pollutant outputs of BOD and TSS are incorporated into the analysis along with marketed inputs and outputs to provide a more accurate representation of the production technology in the industry.[5] A panel data set for the 1970-1993 period covering four regional industries, namely Quebec, Ontario, British Columbia, and the Atlantic and Prairies regions is employed.[6] The results

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[5] Changes in air pollutant outputs were not included because matching data on these were not available.
[6] All the Atlantic and Prairies provinces were lumped into one because complete data was not available for individual provinces in these regions. Statistics Canada does not reveal certain statistics for certain provinces for confidentiality reasons.

reported in this article indicate the importance of taking the benefits of pollution abatement activities into account in the analysis of productivity performance.

The paper is organized as follows. The next section discusses the input distance function and the input-based measures of technical efficiency, technical change and the Malmquist productivity index employed for the analysis. The functional form and the methods used for the estimation of the input distance function parameters are also discussed in that section. In Section 3, the results obtained from both the conventional (ignoring undesirable outputs) and the environmentally sensitive (including desirable outputs) approaches are presented and discussed. The results consistently indicate that the conventional approach underestimates the productivity improvement that has occurred in the Canadian pulp and paper industry. In Section 4, the paper is summarized and concluded.

## 2. REPRESENTATION OF TECHNOLOGY AND PRODUCTIVITY MEASURES

The incorporation of pollutant outputs into the analysis requires the use of production models that can handle multi-output technologies. Since we rarely have market or shadow prices for pollutant outputs we also require methods that can be employed with information on the quantities but not on the prices of pollutant outputs.[7] Both input and output distance functions are convenient for modelling multi-output technologies and both require information on input and output quantities. Following Hailu and Veeman (2000), input-based measures and input distance functions were chosen for this analysis.[8]

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[7] Some researchers have used pollutant output prices obtained from pollution abatement estimates (e.g. Pittman 1983) or from contingent valuation of pollution damage values (e.g. Repetto et al 1996) to compute productivity indexes that incorporate pollutant outputs.

[8] Fare et al (1993) and Coggins and Swinton (1996) have employed output distance functions. We chose an input distance function because input-based measures can be calculated more easily from these. Input-based measures are

For the case of a production technology using N inputs to produce M marketable and pollutant outputs, Shephard's (1953, 1970) input distance function can be defined as follows,

$$\Psi(\mathrm{u}, \mathrm{x}, \mathrm{t}) = \sup_{\theta} \{\theta : (\mathrm{u}, \frac{\mathrm{x}}{\theta}) \in \mathrm{Y}(\mathrm{t}), \theta \in \mathrm{R}_{+}\} \qquad (1)$$

where: *x* and *u* are, respectively, the input and output vectors; *t* is the time trend variable; and Y(t) is the technology (or production possibility) set at time *t*. In other words, the value of the input distance function measures the maximum amount by which the input vector can be deflated, given the output vector. Thus, by definition, the reciprocal of the value of the input distance function provides the standard input-based Farrell (1957) measure of technical efficiency (TE) as shown in (2). A value greater than one for the input distance function indicates that the observed input-output vector is technically inefficient.

$$\mathrm{TE}_{\mathrm{x}}(\mathrm{u}, \mathrm{x}, \mathrm{t}) = \frac{1}{\Psi(\mathrm{u}, \mathrm{x}, \mathrm{t})} \qquad (2)$$

The input distance function has the following properties: it has a finite value for $u \geq 0$; it is an increasing and continuous function of x for $u \in \mathrm{R}^{M}_{+}$; it is concave and homogeneous of degree one in x; it is an upper semi-continous and quasi-concave function of *u*. See Shephard (1970) or Fare and Primont (1995) for more on the characteristics of the function.

We will also distinguish between the first derivative or monotonicity properties of the input distance function with respect to desirable and undesirable outputs. By definition, the distance value of the distance function measures the maximum proportion by which all inputs can be proportionally reduced without a change in the output vector. The distance function should,

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as appropriate in the presence of undesirable outputs as they are without. See Hailu and Veeman (2000) for more on these. Several other researchers have used different variants of the data envelopment analysis model to incorporate pollutant outputs. See, for example, Ball et al (1994), Chung et al (1997), Fare et al (1989), Tyteca (1997) and therefore, be non-decreasing in inputs and non-increasing in desirable (or freely disposable) outputs. On the other hand, a reduction in pollutant outputs requires the use of inputs for abatement, other outputs remaining the same. Therefore, the input distance function should be non-decreasing in pollutant outputs. These conditions are incorporated into the estimation of the parameters of the distance function.

An input-based Malmquist index of productivity growth (Caves, Christensen and Diewert 1982b) is derived from the input distance function. This Malmquist index can be decomposed into technical efficiency (TE) and technical change (TC) components (Fare et al 1994). In terms of input-conservation, technical change is defined as the rate at which inputs can be proportionally decreased over time without change in output levels. This measure reduces to a convenient form, viz., the derivative of the distance function with respect to time, i.e.

$$TC_x(u,x,t) = \frac{\partial \Psi(u,x,t)}{\partial t} \qquad (3)$$

The calculation of the growth rate in the Malmquist productivity growth index from period *t* to period *t+1* was carried out as follows:

$$\begin{aligned} \mathit{ln}\,M(x^{t+1},x^t,u^{t+1},u^t) = \{&\mathit{ln}\,\Psi(u^t,x^t,t) - \mathit{ln}\,\Psi(u^{t+1},x^{t+1},t+1)\} + \\ &\{TC_x(x^{t+1},u^{t+1},t+1) + TC_x(x^t,u^t,t)\}/2 \qquad (4) \end{aligned}$$

The first term in square brackets measures the rate of improvement in technical efficiency between period t and t+1. The second term represents the estimated rate of technical change over that period obtained by averaging the technical change growth rates for periods t and t+1. This formula was employed by Nishimuzi and Page (1982), Perelman (1995) and Hailu and Veeman (2000).

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Yaisawarng and Klein (1994).

The translog functional form (Christensen, Jorgenson and Lau 1973) was chosen for the input distance function. Mathematical or goal programming methods (Aigner and Chu 1968)[9] were used to estimate the parameters of the distance function. The sum of deviations of the values of the distance function from unity were minimized subject to monotonicity, homogeneity and symmetry conditions. The value of the input distance was also required to be equal to or greater than unity for all the 36 observations to ensure that the estimated technology supports the empirical observations in the sample as feasible. The linear programming problem was solved using programs written in GAMS. The estimation procedures used here are similar to those used in Hailu and Veeman (2000) who estimate an input distance function for the national pulp and paper industry. Goal programming methods were chosen over econometric ones because the monotonicity restrictions required to distinguish between desirable and undesirable outputs can be incorporated easily with goal programming. Additional details about the estimation procedure are provided in the Appendix B.

## 3. RESULTS AND DISCUSSION

A panel data set covering the period from 1970 to 1993 for four regions, namely Quebec, Ontario, British Colombia and the Atlantic and Prairie was used in this study. The data set includes pulp and paper output, two water pollutant outputs (BOD and TSS), and five inputs. The input categories identified include the following: energy, virgin fiber, non-wood materials and services, production and administration labour, and capital. Some summary statistics for the data used are reported in Table I. Input and output components in each of the input and output quantity categories were aggregated using the Multilateral Tornqvist index developed by Caves,

[9] See also Serot (1993), Fare et al (1993), Coggins and Swinton (1996) and Hailu and Veeman (2000).

Christensen and Diewert (1982b) resulting in a scaled data set with the 1970 values for Ontario set at 1.00. The multilateral index allows us to compare quantities across space and time simultaneously. The BOD and TSS data were obtained by special request from the Canadian Pulp and Paper Association. The rest of the input and output data were obtained from Statistics Canada, including from Statistics Canada catalogues No. 25-202, No. 36-204 and No. 36-250.

TABLE I.
Changes in Pulp and Paper Industry Desirable and Undesirable Output Rates (1970-93)

| Variable | 1970 Value | Mean 1970-93 Value | 1993 Value | Average Annual Growth, 1970-93 (%) | Cumulative change for 1970-1993 (%) |
|---|---|---|---|---|---|
| Pulp and paper output ($10^6$ 1986 $) | | | | | |
| Quebec | 3554 | 3849 | 3947 | 0.46 | 11.08 |
| Ontario | 2435 | 2401 | 2467 | 0.06 | 1.32 |
| Atlantic & Prairies | 2565 | 3242 | 3268 | 1.05 | 27.39 |
| BC | 967 | 1760 | 2890 | 4.76 | 198.90 |
| BOD output ($10^3$ metric tonnes) | | | | | |
| Quebec | 401.04 | 310.85 | 130.92 | -4.87 | -67.35 |
| Ontario | 273.65 | 155.66 | 60.90 | -6.53 | -77.75 |
| Atlantic & Prairies | 225.07 | 140.05 | 70.21 | -5.06 | -68.81 |
| BC | 217.28 | 147.85 | 49.86 | -6.40 | -77.05 |
| TSS output ($10^3$ metric tonnes) | | | | | |
| Quebec | 212.32 | 121.86 | 35.71 | -7.75 | -83.18 |
| Ontario | 136.82 | 46.00 | 19.03 | -8.58 | -86.09 |
| Atlantic & Prairies | 122.59 | 74.91 | 36.68 | -5.25 | -70.07 |
| BC | 192.68 | 93.22 | 37.39 | -7.13 | -80.59 |
| BOD rates (Kg/MT of woodpulp) | | | | | |
| Quebec | 68.00 | 50.00 | 22.00 | -4.91 | -67.65 |
| Ontario | 75.99 | 42.04 | 16.00 | -6.77 | -78.95 |
| Atlantic & Prairies | 54.90 | 27.26 | 11.27 | -6.89 | -79.48 |
| BC | 72.16 | 39.32 | 10.39 | -8.43 | -85.61 |
| TSS rates (Kg/MT of woodpulp) | | | | | |
| Quebec | 36.00 | 19.96 | 6.00 | -8.21 | -83.33 |
| Ontario | 38.00 | 12.63 | 5.00 | -8.63 | -86.64 |
| Atlantic & Prairies | 29.90 | 14.58 | 5.89 | -6.30 | -80.31 |
| BC | 63.99 | 24.98 | 7.79 | -11.89 | -87.83 |

The data were used to estimate a translog form of input distance function in (1). Then technical efficiency, technical change and productivity growth estimates were generated using the formulae in equations (2), (3) and (4), respectively. The results obtained by following the conventional approach of ignoring pollutant outputs are discussed below, followed by the estimates obtained under an environmentally sensitive approach.

### *3.1. Results from a Conventional Approach*

The conventional estimates of technical efficiency indicate the presence of significant differences among the four regions. Efficiency levels are lowest in Quebec, which has an average score of 0.85 for the period from 1970 to 1993. The efficiency level in Quebec was just below 0.90 in the beginning of the period but fell during the first oil crises period reaching below 0.80 in 1975. The slow recovering in efficiency that was achieved in the period from 1976 to 1981 was again followed by reductions in efficiency, especially during the macroeconomic recessions of the early 1980s and late 1980s. The reductions in efficiency in these periods of macroeconomic recession are also evident in the trends for the other regions. Looking at the entire period covered in the study, Ontario had the highest levels of average technical efficiency, at 0.93, with BC and the Atlantic and Prairies regions following with scores of 0.92 and 0.89.

In terms of changes in the degree of technical efficiency over time, there was little change for most regions on average, except for the Atlantic and Prairies whose relative technical efficiency level fell at an average annual rate of –1.01 percent. The overall trend indicates a decline in technical efficiency at an average annual rate of –0.25 percent.

The average rate of technical change was positive in the Atlantic and Prairies but negative in all other regions. The decline was strongest in Quebec, with an average rate of –1.18 percent per year for technical efficiency. The increase in the Atlantic and Prairies was also meagre, at a rate of 0.08 percent per year. As a result, the results indicate that the average rate of the Malmquist productivity growth defined in (4), was negative in all regions, with the least decline occurring in BC (-0.03 percent). The rates of decline for Quebec, Ontario and the Atlantic and Prairies were, respectively, -1.1, -0.91 and –0.90 percent. The estimates discussed above are summarized in Tables A1 and A2.

### *3.2. Results from Environmentally Sensitive Approach*

There is a dramatic change in productivity growth estimates, when the input distance function and the productivity measures are re-estimated in environmentally sensitive ways. The results from the estimation of the input distance function with the marketed inputs and outputs discussed above as well as the two water pollutants of BOD and TSS, indicate that productivity growth in most regions has been positive rather than negative as suggested by the conventional measures discussed above. In the case of Ontario, BC and the Atlantic and Prairie regions, the average rates of both technical change and productivity growth are positive. BC had an average annual rate of productivity growth of 1.14 % for the period from 1970 to 1993. The rates for Ontario and the Atlantic and Prairie regions were, respectively, 0.05% and 0.07%. The average annual productivity growth rate for Quebec was negative (-0.85%), although it was higher than the estimates obtained from the conventional approach that ignored pollutant outputs.

These changes in the productivity growth estimates are mainly due to the differences in technical change estimates obtained from the conventional and the environmentally sensitive analysis. The technical change estimates for Ontario, BC and Atlantic and Prairie regions were estimated to be 0.05%, 1.13% and 0.81%, respectively. For, Quebec, this estimates was an average annual rate of –0.76%. Technical efficiency estimates remained similar between these two approaches. In particular, the average TE estimates for Quebec, Ontario, BC and the Atlantic and Prairie regions were, respectively, 0.84, 0.95, 0.90 and 0.94. The absence of much variation in the estimates of TE from the two approaches is not inconsistent with our expectations. This is because the pollution abatement levels have changed in all regions over time. Since the TE estimates are based on comparison of individual regions against the frontier or the technology for a given period, we cannot expect much change in TE estimates unless the regions have progressed at different rates in their pollution abatement activities. But the changes in pollution abatement levels over time are reflected in the higher estimates of technical change discussed above.

We see these differences between conventional and environmentally sensitive estimates because the latter credits the producer for the reduction of pollutant output while the conventional one does not. The specification of the technology treats desirable and undesirable outputs asymmetrically, with pollutant outputs as bads that cannot be freely disposed. The input-based estimates of technical efficiency and technical change (and also the input-based Malmquist index) reflect that asymmetry. The technical efficiency measure, for example, is equal to the reciprocal of the input distance function. Since the input distance function is non-increasing in desirable outputs and non-decreasing in undesirable outputs, the measure of technical efficiency is non-decreasing in desirable outputs and non-increasing in undesirable outputs. That is the technical efficiency score credits the producer for the production of more desirable outputs and for reductions in undesirable outputs. Similarly, the technical change measure defined in (3) credits the producer for reductions in pollutant outputs. Since the Malmquist productivity growth measure defined in (4) is a composite of the technical efficiency and technical change components, it also treats desirable outputs and pollutant outputs asymmetrically by crediting the producer for the reduction in pollutant outputs and for increases in desirable outputs.

Since the input-based measure is based on the input saving that could have been achieved if outputs (desirable and undesirable) were to be held constant, inputs used for the purpose of pollution abatement are recognized by the environmentally sensitive input-based measure as inputs that could have been saved if there were no pollution abatement. Therefore, if an increasing percentage of inputs are being used for pollution abatement, the environmentally sensitive input-based measure recognizes the fact that a higher percentage of inputs could have been saved if there were no pollution abatement. Therefore, the producer is credited accordingly for his/her investment in pollution abatement when the environmentally sensitive input-based measure is used. The conventional input-based measure, on the other hand, fails to take this very fact into account since it ignores changes in pollutant outputs. This is the intuition behind the differences in the results reported in the paper.

## 4. SUMMARY AND CONCLUSION

A parametric input distance function was used to estimate technical efficiency, technical change and productivity growth in four Canadian regional pulp and paper industries, namely, Quebec, Ontario, British Columbia, and the Atlantic and Prairie regions. The input distance function was estimated using panel data for the period from 1970 to 1993. The input and output data consisted of multilateral index series for each of the five inputs (i.e., energy, labour, fiber, non-wood materials and capital) and three outputs. The three outputs considered include the desirable outputs of pulp and paper as well as undesirable outputs of BOD and TSS. The pulp and paper industry is the most important source of industrial water pollution in Canada; and this pollution takes mainly the form of BOD and TSS effluent discharges. The industry has invested heavily in pollution abatement, primarily aimed at reducing water pollution over the period of the last three decades. Conventional productivity growth estimates that ignore changes in environmental effects or pollution output cannot, therefore, provide an accurate indication of changes in the performance of this industry. For industries, like the Canadian pulp and paper industry, that have had significant changes in their environmental effects, we need to incorporate pollutant output to get more accurate measures of productivity growth. This study compares productivity performance measures for the four regions estimated both under the conventional and environmentally sensitive approaches.

The results, from both the conventional and environmentally sensitive, approaches indicate that there are substantial differences in the degree of technical efficiency among the regional pulp and paper industries. Ontario had the highest level of average technical efficiency, followed by the Atlantic and Prairie regions. Quebec had the lowest average technical efficiency at about 84%. There was little difference between the conventional and environmentally adjusted estimates of technical efficiency, as the measures are based on a comparison of a given observation against the frontier for that year, while the source of divergence between conventional and environmentally sensitive measures has been the increasing investment in pollution abatement over time. As a result, technical change and productivity growth estimates increase dramatically when pollutant outputs are incorporated into the analysis.

The average conventional annual productivity growth estimates for Quebec, Ontario, BC and the Atlantic and Prairie regions are –1.10%, -0.91%, -0.90% and –0.03%, respectively, while the corresponding estimates obtained from an environmentally sensitive approach that recognizes reductions in the industries' water pollutant output levels stand at –0.85%, 0.05%, 0.07%, 1.14%. Averaging over all regions, the conventional measure indicates that productivity in the Canadian pulp and paper industry has been declining at the rate of –0.74% per year. The corresponding environmentally sensitive figure is 0.10% per year. The main conclusion of this study is that, in industries that have witnessed significant changes in pollution abatement, performance measures that ignore environmental effects provide a distorted measure of performance. This is because conventional measures, by focusing only on marketed output and inputs, credit the industry for changes in desirable outputs but not for changes in undesirable outputs or undesirable outputs. Researchers and policy makers are advised to use environmentally sensitive measures whenever that is possible.

## APPENDIX A: SUMMARY OF RESULTS

TABLE A1. Regional Pulp and Paper Industry Efficiency, Technical Change and Total Factor Productivity Estimates (1970-1993)

| Productivity Measure | Conventional Measures | Environmentally Adjusted |
|---|---|---|
| Technical Efficiency (TE) | | |
| Quebec | 0.85 | 0.84 |
| Ontario | 0.93 | 0.95 |
| Atlantic and Prairies | 0.92 | 0.94 |
| BC | 0.89 | 0.90 |
| All Regions | 0.90 | 0.91 |
| Rate of change in TE (EC) | | |
| Quebec | 0.06% | -0.10% |
| Ontario | 0.00% | 0.00% |
| Atlantic and Prairies | -1.01% | -0.76% |
| BC | -0.06% | -0.03% |
| All Regions | -0.25% | -0.22% |
| Technical Change (TC) | | |
| Quebec | -1.18% | -0.76% |
| Ontario | -0.93% | 0.05% |
| Atlantic and Prairies | 0.08% | 0.81% |
| BC | -0.01% | 1.13% |
| All Regions | -0.51% | 0.31% |
| TFP Growth Rate (PRR) | | |
| Quebec | -1.10% | -0.85% |
| Ontario | -0.91% | 0.05% |
| Atlantic and Prairies | -0.90% | 0.07% |
| BC | -0.03% | 1.14% |
| All Regions | -0.74% | 0.10% |

TABLE A2. Technical Efficiency Estimates for Regional Pulp and Paper Industries.

| | Conventional Analysis | | | | Environmentally Sensitive Analysis | | | |
|---|---|---|---|---|---|---|---|---|
| | Quebec | Ontario | Atlantic & Prairies | BC | Quebec | Ontario | Atlantic & Prairies | BC |
| 1970 | 0.88 | 1.00 | 0.98 | 1.00 | 0.90 | 1.00 | 1.00 | 1.00 |
| 1971 | 0.81 | 0.96 | 0.86 | 0.90 | 0.81 | 0.96 | 0.89 | 0.93 |
| 1972 | 0.82 | 0.95 | 0.84 | 0.85 | 0.82 | 0.96 | 0.87 | 0.89 |
| 1973 | 0.83 | 1.00 | 0.88 | 0.87 | 0.83 | 1.00 | 0.88 | 0.94 |
| 1974 | 0.76 | 0.98 | 0.90 | 0.94 | 0.77 | 0.97 | 0.90 | 1.00 |
| 1975 | 0.80 | 1.00 | 1.00 | 0.91 | 0.78 | 1.00 | 1.00 | 0.97 |
| 1976 | 0.83 | 0.92 | 1.00 | 0.81 | 0.83 | 0.92 | 0.99 | 0.85 |
| 1977 | 0.90 | 0.94 | 0.96 | 0.85 | 0.91 | 0.95 | 0.97 | 0.88 |
| 1978 | 0.93 | 0.94 | 0.94 | 0.81 | 0.93 | 0.93 | 0.94 | 0.83 |
| 1979 | 0.93 | 0.95 | 0.96 | 0.83 | 0.92 | 0.93 | 0.97 | 0.87 |
| 1980 | 0.85 | 0.93 | 0.99 | 0.81 | 0.84 | 0.92 | 1.00 | 0.85 |
| 1981 | 0.92 | 0.93 | 0.92 | 0.78 | 0.91 | 0.94 | 0.96 | 0.83 |
| 1982 | 0.90 | 0.92 | 0.94 | 0.80 | 0.87 | 0.97 | 1.00 | 0.83 |
| 1983 | 0.82 | 0.81 | 0.92 | 0.95 | 0.77 | 0.87 | 0.98 | 0.96 |
| 1984 | 0.84 | 0.84 | 0.92 | 0.95 | 0.81 | 0.90 | 0.97 | 0.97 |
| 1985 | 1.00 | 0.92 | 0.87 | 1.00 | 1.00 | 0.97 | 0.93 | 1.00 |
| 1986 | 0.83 | 0.92 | 0.85 | 0.97 | 0.81 | 1.00 | 0.90 | 0.97 |
| 1987 | 0.83 | 0.92 | 0.96 | 0.85 | 0.81 | 0.98 | 0.99 | 0.83 |
| 1988 | 0.85 | 0.92 | 1.00 | 0.98 | 0.84 | 0.97 | 1.00 | 0.93 |
| 1989 | 0.69 | 0.86 | 0.92 | 0.86 | 0.67 | 0.91 | 0.90 | 0.81 |
| 1990 | 0.74 | 0.82 | 0.86 | 0.86 | 0.72 | 0.84 | 0.86 | 0.82 |
| 1991 | 0.93 | 0.89 | 1.00 | 0.82 | 0.92 | 0.92 | 1.00 | 0.84 |
| 1992 | 0.82 | 0.95 | 0.69 | 0.90 | 0.80 | 1.00 | 0.74 | 0.90 |
| 1993 | 0.89 | 1.00 | 0.78 | 0.99 | 0.88 | 1.00 | 0.84 | 0.99 |
| Average | 0.85 | 0.93 | 0.92 | 0.89 | 0.84 | 0.95 | 0.94 | 0.90 |

## APPENDIX B: SPECIFICATION AND ESTIMATION OF INPUT DISTANCE FUNCTION

The following translog specification was used for the input distance function representation of the pulp and paper production technology:

$$\begin{aligned}
\ln \Psi(u^{kt},x^{kt},t) = {} & \alpha_o + \sum_{n=1}^{N} \alpha_n . ln\, x^{kt}{}_n + \sum_{m=1}^{M} \beta_m . ln\, u^{kt}{}_m \\
& + (0.5) \sum_{n=1}^{N} \sum_{n'=1}^{N} \alpha_{nn'} . ln\, x^{kt}{}_n . ln\, x^{kt}{}_{n'} \\
& + (0.5) \sum_{m=1}^{M} \sum_{m'=1}^{M} \beta_{mm'} . ln\, u^{kt}{}_m . ln\, u^{kt}{}_{m'} \qquad (B1) \\
& + (0.5) \sum_{n=1}^{N} \sum_{m=1}^{M} \gamma_{nm} . ln\, x^{kt}{}_n . ln\, u^{kt}{}_m \\
& + \alpha_t . t + (0.5) . \alpha_{tt} . t^2 \\
& + \sum_{n=1}^{N} \alpha_{nt} . t . ln\, x^{kt}{}_n + \sum_{m=1}^{M} \beta_{mt} . t . ln\, u^{kt}{}_m
\end{aligned}$$

where: *k* indexes the regions; n indexes the vector of inputs such that the subscripts 1,2,...,5 represent, respectively, energy, wood, non-wood materials and services, production and administration labour, and capital; *m* indexes the output vector of the firm such that 1 represents the marketable outputs of pulp and paper, respectively, while 2 and 3 represent the pollutant outputs BOD and TSS; and *t* denotes the time period variable.

Mathematical programming methods were used to estimate the parameters of the input distance function in equation (B1). The mathematical programming approach to parameter estimation (also known as goal programming) was first used by Aigner and Chu (1968). The method relies on the minimization of the sum of deviations of the values of the function from the production frontier that is being estimated. Goal programming does not provide statistical measures of goodness of fit. However, since it is based on mathematical programming methods, it is a very flexible method that allows us to impose not only equality but also inequality restrictions very easily. The ability to impose inequality restrictions is of prime importance in the case of this study because the asymmetric treatment of desirable and undesirable outputs in the specification of the technology requires the imposition of weak inequality restrictions on the first derivative signs of the input distance function. In this sense, the goal programming approach to parameter estimation allows us to build in sophistication in the specification of the systematic component of the function much more easily than is possible with econometric techniques. The linear programming approach to parameter estimation has been used in several recent studies (e.g., Serot 1993; Fare et al 1993; Coggins and Swinton 1996; and Hailu and Veeman 2000).

The objective in our goal programming problem is to choose the set of parameter estimates that minimizes the sum of deviations of the logarithmic values of the distance function from zero. Monotonicity, homogeneity and symmetry conditions are imposed as constraints. An additional constraint imposed on the problem is the requirement that the value of the input distance should be equal to or greater than unity for all the observed input-output combinations (or for the k=1,..,4 regions and t=1,…,24 time periods). That is, the estimation takes the following form:

$$Minimize_{(\alpha,\beta,\gamma)} \sum_{k=1}^{4}\sum_{t=1}^{24} ln\,\Psi(u^{kt}, x^{kt}, t) \qquad (B2)$$

Subject to the following constraints:

$$ln\Psi(u^{kt}, x^{kt}, t) \geq 0, \quad t = 1,...,24, k = 1,...,4 \qquad (B3)$$

$$\frac{\partial ln\Psi(u^{kt}, x^{kt}, t)}{\partial x^{kt}{}_n} \geq 0, \; t = 1,...,24, \, k = 1,...,4, \, n = 1,...,5 \qquad (B4)$$

$$\frac{\partial ln\Psi(u^{kt}, x^{kt}, t)}{\partial u^{kt}{}_m} \leq 0, \; t = 1,...,24, \, k = 1,...,4, \, m = 1 \qquad (B5)$$

$$\frac{\partial ln\Psi(u^{kt}, x^{kt}, t)}{\partial u^{kt}{}_m} \geq 0, \; t = 1,...,24, \, k = 1,...,4, \, m = 2,3 \qquad (B6)$$

$$\sum_{n=1}^{5} \alpha_n = 1 \qquad (B7a)$$

$$\sum_{n=1}^{5} \alpha_{nn'} = 0, \; n' = 1,...,5 \qquad (B7b)$$

$$\sum_{n=1}^{5} \gamma_{nm} = 0, \; m = 1,...,3 \qquad (B7c)$$

$$\sum_{n=1}^{5} \alpha_{nt} = 0, \qquad (B7d)$$

$$\alpha_{nn'} = \alpha_{n'n,}, \quad n, n' = 1,...,5 \qquad (B8a)$$

$$\beta_{mm'} = \beta_{m'm,}, \; m, m' = 1,...,3 \qquad (B8b)$$

The first set of constraints (B3) requires that the value of the estimated input distance function be unity or higher at observed input-output combinations; that is, these constraints ensure that the estimated function identify observed input-output combinations as feasible or as observations within the technology frontier. The second set of constraints (B4) imposes the monotonicity condition that the distance function be non-decreasing in inputs. The third set of constraints (B5) requires that the function be a non-increasing function of desirable outputs, while the constraints in (B6) ensure that the estimated input distance function is non-decreasing in undesirable outputs. Thus, the constraints in (B5) and (B6) are needed to incorporate the fundamental asymmetry between desirable and undesirable outputs into the characterization of the production technology: namely, that desirable outputs are freely disposable but pollution abatement is costly. The remaining set of constraints ensure the linear homogeneity in inputs of the function (B7) and the parameter symmetry conditions for the translog functional form (B8).

In other words, the parameter estimation for the input distance function with pollutant outputs is carried out by minimizing the sum of deviations from unity subject to 897 constraints. These are 96 (i.e., for 24 years and four regions) feasibility constraints; 778 monotonicity constraints relating to inputs (480), desirable outputs (96) and pollutant outputs (194); 10 linear homogeneity conditions; and 13 translog symmetry restrictions. While the linear homogeneity and translog symmetry restrictions are equality restrictions applied directly on the parameters being estimated, it is not easy to interpret the remaining 876 weak inequality restrictions in terms of gains in degrees of freedom (in the literal sense of the term) because these constraints contribute to the estimation indirectly through restrictions on functions of the parameters (e.g. derivatives, etc.) rather than as direct restrictions on the parameter values themselves. Nonetheless, these 876 inequality constraints amount to a large amount of prior information being employed to narrow down the parameter space and to guide the estimation so that the chosen parameters locate the technology in such a way that the corresponding theoretically desirable properties are satisfied at all data points. The estimation procedures employed here follow those in Hailu and Veeman (2000).

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