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Environmentally sensitive productivity analysis of the Canadian pulp and paper industry, 1959-1994: an input distance function approach.

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Environmentally Sensitive Productivity Analysis of the Canadian Pulp and Paper Industry, 1959–1994:

An Input Distance Function Approach

by

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ABSTRACT

Most empirical studies of productivity to date have considered only marketed or desirable outputs and have neglected changes in the production of pollutant outputs. This neglect of negative externalities is also evident in studies that have attempted to assess the impact of environmental regulation on productivity growth. This study employs parametric input distance functions that incorporate both desirable and undesirable outputs to provide a more complete representation of the production technology from which environmentally sensitive productivity and efficiency measures can be generated. This framework can also be used to generate information on the shadow prices of pollutant outputs or pollution abatement costs to producers that are useful inputs for environmental policy making. The method was applied to data from the Canadian pulp and paper industry for the period from 1959 to 1994. Four desirable outputs, two water pollutant outputs (BOD and TSS) and seven inputs were identified in the estimation of the input distance function. Our results indicate that productivity measures that ignore pollutant outputs substantially underestimate the performance of the industry. Our environmentally sensitive approach indicates that the total factor productivity of the industry has been growing at the rate of 1.00 percent per year over the period from 1959 to 1994, considerably higher than the 0.19 percent per year estimate obtained without considering pollutant outputs. Our shadow price estimates, however, indicate that the cost to producers of pollution control has been rising. The main conclusion of this study is that productivity improvement, from the social viewpoint, has been stronger than conventional measures would suggest.

INTRODUCTION

Conventional measures of productivity and efficiency inevitably lead to conclusions that are biased against environmental protection. These measures account for saleable or marketed outputs and inputs while undesirable outputs or externalities are ignored. Therefore, the costs of pollution abatement as inputs are included while the social benefits of improved environmental quality are generally ignored. Such asymmetric treatment of marketed "goods" and "bads" leads to distortions in our assessment of changes in social well being and distorted pictures of relative economic performance. This also leads to misguided policy recommendations (Fare et al. 1993; Repetto et al. 1996, 1997).

This study uses input distance functions to provide a framework for a more complete representation of production technology in the Canadian pulp and paper industry, from which environmentally sensitive productivity and efficiency measures can be generated. Both desirable (marketable) outputs and undesirable outputs are incorporated into the analysis. The approach has the additional advantage that it allows us to estimate producer shadow prices of pollutant outputs. The producer abatement cost information thus generated is useful for evaluating and guiding environmental policy and for further economic analysis.

Pulp and paper is Canada's largest manufacturing industry measured in terms of employment, value added and net exports (CPPA 1996). The industry has also been a significant source of water pollution, accounting for about 50 percent of the waste dumped into the nation's waters (Sinclair 1990). Biological oxygen demand (BOD) and total suspended solids (TSS) are the two major water pollutants from the industry. Organic matter contained in mill effluents stimulates algal growth and consumes dissolved oxygen thereby reducing the ability of the water to support aquatic life. Suspended solids increase turbidity, upset aquatic habitat and ruin fish spawning beds. The industry has spent large sums of money to reduce pollution output. As a result, BOD and TSS rates have declined from 102 and 118 kilograms per tonne of wood pulp produced to only 13 and 6, respectively, in the period between 1959 to 1994.

Some attempts have been made in the literature to incorporate pollutant outputs in efficiency and productivity analysis (Pittman 1983; Fare et al. 1989b; Fare et al. 1993; Coggins and

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Swinton 1996; Repetto et al. 1996). Pittman (1983) provided the earliest attempt at incorporating undesirable outputs in efficiency measurement. He used shadow prices calculated from abatement costs in his computation of enhanced Caves et al. (1982a) multilateral productivity indexes to compare the productive efficiencies of a sample of 30 pulp and paper mills in Wisconsin. More recently, a study by Repetto et al. (1996) used adjusted non-market valuation estimates of the marginal pollution damage values to compute adjusted productivity indexes for three US industries, including the pulp and paper industry.

These index number approaches depend on external damage value estimates (as in the Repetto et al. study) or on the estimation of pollutant shadow prices from abatement expenditure by producers (as in the study by Pittman). Estimating abatement costs is likely to become less and less practical because it is increasingly difficult to distinguish between "productive" and pollution abatement expenditures on capital or other inputs. Pollution damage estimates are unlikely to be available on a yearly basis. Moreover, the accuracy and transferability across regions and time periods of non-market valuations of pollution damages are similarly open to question.

The use of distance functions incorporating both desirable and pollutant outputs can help overcome the problems associated with the index number approaches discussed above. Fare et al. (1993) and Coggins and Swinton (1996) use output distance functions for this purpose. Fare et al. (1993) used Pittman's data to estimate an output distance function from which they calculated efficiency measures and producer specific shadow prices for pollutant outputs. Coggins and Swinton (1996) also use the output distance function method to estimate sulphur dioxide shadow prices for 14 coal-burning electric plants in Wisconsin.

INPUT DISTANCE FUNCTION SPECIFICATION OF TECHNOLOGY

This study uses input distance functions to analyze productivity trends in the Canadian pulp and paper industry in environmentally sensitive ways. Both input and output distance functions are capable of handling multi-output technologies and share the features described above. Nonetheless, input distance function were chosen for this analysis because the efficiency interpretation of the input distance function values remains unambiguous even when pollutant outputs are incorporated

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into the analysis.

For the case of a production technology using N inputs to produce M marketable and pollutant outputs, following Shephard (1953, 1970) and Fare and Primont (1995) the input distance function $D: R_+^N \times R_+^M \to R_+ \cup \{+\infty\}$ can be defined as follows, after the introduction of a time trend in our particular case to capture technological change,

$$D(u,x,t) = \sup_\theta \left\{ \theta : (u, \frac{x}{\theta}) \in Y(t), \theta \in R_+ \right\} \tag{1}$$

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. It measures the minimal proportional contraction of the input vector required to bring it to the frontier of the input requirement set for the output vector.

Thus, by definition, the reciprocal of the value of the input distance function provides an input-based Farrell (1957) measure of technical efficiency, i.e.

$$TE_x(u,x,t) = \frac{1}{D(u,x,t)} \tag{2}$$

In other words, (1-TE) measures the proportion by which costs would be reduced by improving technical efficiency, without reducing output. A value greater than one for the input distance function indicates that the observed input-output vector is technically inefficient.

The input distance function has the following properties: it has a finite[2] value for $u \geq 0$; it is an increasing continuous function of x for $u \in R^M_+$; it is concave and homogeneous of degree one in x; it is an upper semi-continuous and quasi-concave function of u. If inputs are freely disposable[3], the input distance function provides a complete characterization of the production technology. See Shephard (1970) or Fare and Primont (1995), for example, for more on the characteristics of the function.

We will also distinguish between the derivative properties of the input distance function with respect to desirable and undesirable outputs. By definition, the distance value of the distance

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[2] $D(u,x,t)=0$ if $(u,x) \notin \Delta = \{(u,x)| u \geq 0, x \geq 0, \exists \lambda > 0 \text{ such that } (u,\lambda x) \in Y(t)\}$. And $D(0,x,t) = +\infty$.
[3] Free disposability of inputs simply means there are no holes in the input requirement set L(u), i.e. $x \in L(u) \Rightarrow x/\delta \in L(u) \forall \delta \in$

function measures the maximum proportion by which all inputs can be proportionally reduced without a change in the output vector. The distance function should, 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 as described below.

We can define and measure productivity growth either in terms of output-enhancement or in terms of input-conservation (see, for example, Caves et al. 1982b; Lovell 1993). These two measures can be related through the returns to scale parameter[4] and are equal when the technology is characterized by constant returns to scale. We will focus on input-based measures of technical efficiency (as the one defined in equation [2] above) and technical change in this study. Unlike output-based measures of productivity growth, input-based measures remain unambiguous measures of technical efficiency and technical change even when undesirable outputs are brought into the analysis.

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 rate is equal to

$$TC_x(u,x,t) = \frac{\partial \ln \zeta}{\partial t}\bigg|_{D(\zeta u,x,t)=\zeta=1}$$

where ζ is a scalar that represents an equiproportionate change in the input vector, x. This measure reduces to a convenient form, viz., the derivative of the distance function with respect to time[5], i.e.

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

The alternative output-based measure of technical change measures the rate at which all outputs could be increased over time without any change in the vector of inputs used, i.e.

(0,1]. See Fare and Primont (1995).

[4] The proportion by which the output vector can be increased, given a vector of inputs, is equal to the product of the returns to scale parameter and the proportion by which inputs can be decreased, given a vector of outputs to be produced.

[5] By simple application of Euler's theorem. This is also intuitive from the very definition of input distance functions.

$$TC_u(\zeta x, \xi u, t) = \frac{\partial \ln \xi}{\partial t}\bigg|_{D(\zeta x, \xi y, t) = \xi = \zeta = 1} \qquad [4]$$

where ξ is a scalar that represents an equiproportionate change in the output vector, u. TC_u is equal to the product of the input-based measure of technical change, TC_x, and the returns to scale measure (RTS). The latter is defined and calculated using the following formula:

$$RTS(u, x, t) = \frac{\partial \ln \zeta}{\partial \ln \xi}\bigg|_{D(\zeta x, \xi y, t) = \xi = \zeta = 1} = \frac{-1}{\nabla_u D(.).u} \qquad [5]$$

Caves et al. (1982b) propose productivity concepts that that are convenient for measuring productivity growth due to technical change and variations in the degree of technical efficiency. For two firms[6], k and l, with output -input vectors (u^k, x^k) and (u^l, x^l) and production technologies given by the input distance functions $D^k(.)$ and $D^l(.)$, respectively, they define the following input-based Malmquist productivity index for comparing the productivity of l to that of k:

$$M(x^l, x^k, u^l, u^k) = \left\{ \frac{D^k(u^k, x^k)}{D^k(u^l, u^l)} \cdot \frac{D^l(u^k, u^k)}{D^l(u^l, u^l)} \right\}^{1/2} \qquad [6a]$$

M is a geometric mean of the two Malmquist input-based productivity indexes, each defined with a different reference technology. The first ratio on the right hand side indicates the minimal input inflation factor such that the inflated input for firm l and the output vector of firm l lie on the production surface of firm k. This ratio is above one if and only if firm l has a higher productivity level than firm k. The second ratio measures the maximal input deflation factor such that the deflated input from k and the output vector of k lie on the production surface of l. This again is above unity if and only if l is more productive than k (Caves et al. 1982b).

The Malmquist index in [6a] can be decomposed into efficiency and technical change components as follows (Fare et al. 1989a):[7]

$$M(x^l, x^k, u^l, u^k) = \frac{D^k(u^k, x^k)}{D^l(u^l, u^l)} \cdot \left\{ \frac{D^l(u^l, x^l)}{D^k(u^l, u^l)} \cdot \frac{D^l(u^k, u^k)}{D^k(u^k, u^k)} \right\}^{1/2} \qquad [6b]$$

The technical change component in [6b] is measured by taking the geometric mean of the shift in

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6The firms k and l could be the same firm at two different points in time, or two firms at the same or different points in time.
7 This is accomplished by first multiplying the term under the square root on the right hand side of equation (6a) by ($D^l(u^l, x^l)$/ $D^k(u^k, x^k))^2$ and then multiplying the whole right hand side by ($D^k(u^k, x^k)$/ $D^l(u^l, x^l)$) to preserve equality.

the technology as measured on the two observations instead of only one.

Obviously, the Malmquist index includes total factor productivity change due to technical change and technical efficiency changes, to the exclusion of production scale effects. The Malmquist index can be calculated from nonparametric technology representations as in data envelopment analysis (DEA) (e.g., Fare et al. 1989a) or from parametrically specified technologies (e.g., Nishimuzi and Page 1982; Perelman 1995).

The calculation of the growth rate in the Malmquist index in [6b] was carried out as follows:

$$\ln M(x'^{t+1}, x', u'^{t+1}, u') = \{\ln D(u', x', t) - \ln D(u'^{t+1}, x'^{t+1}, t+1) \\ + \{TC_x(x'^{t+1}, u'^{t+1}, t+1) + TC_x(x', u', t)\}/2 \tag{7}$$

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) to approximate the Malmquist index growth rate based on their estimation results for a deterministic translog frontier. Perelman (1995) uses the formula to compute Malmquist indexes based on estimation results for a stochastic Cobb-Douglas frontier.

POLLUTANT SHADOW PRICE DERIVATION

Not only does the distance function approach not require external estimates of pollution damage values, but it can also be used to derive producer shadow prices for pollutants that can be usefully used in other analyses or to guide environmental policy. Moreover, the shadow prices are derived under the mild[8] assumption of producer cost minimization behavior.

The cost function is the solution to the following minimization problem:

$$C(u, p, y) = Min_x \{p.x : D(u, x, t) \ge 1, x \in R_+^N\} \tag{8}$$

where $p \in R_+^N$ is the input price vector[9]. Equation [8] is the duality relationship between the cost and input distance functions due to Shephard (1953). Upon a straightforward application of the envelope theorem on the first order conditions, the above cost minimization problem yields the following

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[8] That is by comparison to the assumption of profit maximization.

[9] The second order conditions for this minimization problem are satisfied because the objective function is linear (and, therefore, quasi-convex) and the upper set of the input distance function is convex.

output shadow price formulas:

$$\nabla_u C(u,p,t) = -\Lambda(u,p,t).\nabla_u D(u,x,t)$$
$$= -C(u,p,t).D(u,x,t)$$

[9a]

The first equation follows directly from the first order conditions for the solutions to [8]. The second equation obtains because the Lagrangian multiplier (Λ) is equal to the value of the optimized cost function. The shadow price of a given output is the increase in costs that the production of an additional unit of the output entails. The shadow prices for pollutant outputs will be non-positive, as the input distance function is non-decreasing in pollutant outputs.

If we do not have input prices and cannot accurately estimate the cost of production, we can use the following alternative formula derived from [9a] to calculate the ratio of the shadow price of output i to that of output j:

$$\frac{r_i^*}{r_j^*} = \frac{\partial D(u,x,t)/\partial u_i}{\partial D(u,x,t)/\partial u_j}$$

[9b]

Thus the ratio of the shadow prices is equal to the trade off between the two inputs – how much of units of output j the producer would be willing to forego for the right to emit one more unit of pollutant output i. And if we assume that the market price of u_j equals its shadow price, we can calculate the shadow price (r_i^*) of pollutant output u_i as follows:

$$r_i^* = r_j^* \cdot \frac{\partial D(u,x,t)/\partial u_i}{\partial D(u,x,t)/\partial u_j}$$

[9c]

This formula is used in this study to calculate shadow prices for the two water pollutants, BOD and TSS, included in the estimation of the input distance function. Fare et al. (1993) use a similar procedure to the derivation of shadow prices, but using output distance functions and under the assumption of revenue maximization.

FUNCTIONAL FORM AND ESTIMATION OF INPUT DISTANCE FUNCTION

Functional Form

Flexible functional forms provide a second order approximation to the unknown technology. The flexible translog functional form (Christensen et al. 1973) was chosen for the input distance

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function:

$$
\begin{aligned}
\ln D(u,x,t) \ &= \alpha_o + \sum_{n=1}^{N} \alpha_n . \ln x_n + \sum_{m=1}^{M} \beta_m . \ln u_m \\
&+ (0.5) \sum_{n=1}^{N} \sum_{n'=1}^{N} \alpha_{nn'} . \ln x_n . \ln x_{n'} \\
&+ (0.5) \sum_{m=1}^{M} \sum_{m'=1}^{M} \beta_{mm'} . \ln u_m . \ln u_{m'} \\
&+ (0.5) \sum_{n=1}^{N} \sum_{m=1}^{M} \gamma_{nm} . \ln x_n . \ln u_m \\
&+ \alpha_t t + (0.5) . \alpha_{tt} t^2 \\
&+ \sum_{n=1}^{N} \alpha_{nt} . t . \ln x_n + \sum_{m=1}^{M} \beta_{mt} . t . \ln u_m
\end{aligned}
\qquad [10]
$$

where: n indexes the vector of inputs such that the subscripts 1,2,...,7 represent, respectively, energy, wood residue, pulpwood, non-wood materials, production labour input, administration workers, and capital; m indexes the output vector of the firm such that the 1,2,3 and 4 represent the marketable outputs of wood pulp, newsprint, paper other than newsprint, and paperboards and building boards, respectively, while 5 and 6 represent the pollutant outputs BOD and TSS; and t denotes time trend.

Estimation of Parameters

The parameters of the distance function can be estimated either econometrically or using mathematical programming. Both estimation methods have their own strengths and limitations. Econometric estimation was not possible for this study because of the short length of the time series data that was available compared to the number of parameters to be estimated. Mathematical programming methods were used to estimate the parameters of the input distance function in equation [10].

Mathematical programming (also known as goal programming) methods were first employed by Aigner and Chu (1968) to estimate production function parameters for efficiency analysis. The method has been used in different efficiency and productivity studies since then; see Lovell (1993). Recently, Fare et al. (1993) and Coggins and Swinton (1996) employed linear programming to estimate output distance function parameters. The parameter estimation problem was formulated as

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a linear programming problem. The objective in the problem is to choose the set of parameter estimates that minimizes the sum of deviations of the values of the distance function from unity. 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 36 observed input-output combinations. That is, the estimation takes the form of the following optimization problem:

$$Minimize_{(\alpha,\beta,\gamma)} \sum_{t=1}^{36} \ln D(u,x,t) \qquad [LP1]$$

Subject to the following constraints:

$$\ln D(u,x,t) \geq 0, \quad t = 1,...,36 \qquad [C1]$$

$$\frac{\partial \ln D(u,x,t)}{\partial x_n} \geq 0, \quad t = 1,...36, n = 1,...7 \qquad [C2]$$

$$\frac{\partial \ln D(u,x,t)}{\partial u_m} \leq 0, \quad t = 1,...36, m = 1,...4 \qquad [C3]$$

$$\frac{\partial \ln D(u,x,t)}{\partial u_m} \geq 0, \quad t = 1,...36, m = 5,6 \qquad [C4]$$

$$\sum_{n=1}^{7} \alpha_n = 1 \qquad [C5a]$$

$$\sum_{n=1}^{7} \alpha_{nn'} = 1, \quad n' = 1,...7 \qquad [C5b]$$

$$\sum_{n=1}^{7} \gamma_{nm} = 0, \quad m = 1,...6 \qquad [C5c]$$

$$\sum_{n=1}^{7} \alpha_{nl} = 0 \qquad [C5d]$$

$$\alpha_{nn'} = \alpha_{n'n}, \quad n,n' = 1,...,7 \qquad [C6a]$$

$$\beta_{mm'} = \beta_{m'm}, \quad m.m' = 1,...,6 \qquad [C6b]$$

The first set of constraints [C1] ensures that the estimated function identifies the observation as one that is within the technology frontier (that it is feasible and thus its distance function value should be unity or higher). The second set of constraints [C2] imposes the monotonicity condition

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that the distance function be non-decreasing in inputs. The third set of constraints [C3] requires that the function be a non-increasing function of desirable outputs, while the constraints in [C4] ensure that the estimated input distance function is non-decreasing in the two undesirable or pollutant outputs. The remaining set of constraints ensure the linear homogeneity of the input distance function with respect to inputs [C5] and the symmetry conditions for the translog [C6].

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 555 constraints. These are 36 feasibility constraints; 468 monotonicity constraints relating to inputs (252), desirable outputs (144) and pollutant outputs (72); 15 linear homogeneity conditions; and 36 translog symmetry restrictions. GAMS programs were written and solved to compute the parameter estimates.

The estimation procedures employed here are very similar to those in Fare et al. (1993) and Coggins and Swinton (1996). The only difference is we have imposed monotonicity conditions relating to inputs in addition to those relating to outputs. Our model also includes technological change.

DATA

Industry aggregate time series data for the period from 1959 to 1994 is used. Each of these 36 observations include data on four desirable outputs, two undesirable outputs and seven inputs. The four desirable output categories include net pulp output, newsprint production, paper other than newsprint[10], and paperboards and building boards. The undesirable outputs are biological oxygen demand (BOD) and total suspended solids (TSS) in water effluent from the industry. The seven input categories are: energy, wood residue, pulpwood, materials other than virgin fibre, production labour hours, number of administration workers, and capital. The data and their sources are described in more detail in Hailu (1998).

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[10]This category includes the following: printing and writing papers, wrapping paper, sanitary and specialty papers, and building papers.

RESULTS AND DISCUSSION

The input distance function in [10] was estimated with and without pollutant outputs. This allows us to assess the significance of the inclusion of environmental effects of production activities on our analysis of productivity growth and economic performance in general. The curvature conditions of concavity and quasi-concavity of the input distance function were not imposed for the parameter estimation because that turned the mathematical programming problem into a very large and highly non-linear problem. Therefore, the curvature conditions were tested for after the model was estimated. The estimated input distance functions were found to be concave in inputs and quasi-concave in outputs for all the periods covered in the study, with and without undesirable outputs.

Results from Estimation without Pollutant Outputs

The value of the input distance function was unity or very close to unity for all the years. The average level of productive (technical) efficiency was calculated to be 99.6 percent. Efficiency was at its lowest in the year 1989 when the level of technical efficiency was 96.2 percent, followed by 1976 when the rate was 96.8 percent. The other years when productive efficiency was below 100 percent are 1966, 1967, 1972, 1974, 1979, 1981, 1982, and 1986. The overall level of technical efficiency was estimated to be high partly because the data used are time series data on a single producer (the national pulp and paper industry). The production technology of the industry is characterized by increasing returns to scale. The average returns to scale (RTS) estimate is 1.27.

Since technical efficiency was generally high throughout the period, the Malmquist productivity growth estimates from equation [7] reflect mainly the effects of technical change alone. The average productivity growth rate calculated for the 1959–1994 period is 0.19 percent per year. And most of this productivity growth occurred in the 1980s (0.99 percent per year) and the early 1990s (3.95 percent per year). The 1960s and the 1970s were marked by periods of productivity decline (–1.55 and –0.74 percent per year, respectively) according to the results from input distance function analysis, without pollutant outputs.

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Results from Estimation with Pollutant Outputs

The efficiency and returns to scale estimates from the input distance function with pollutant outputs are similar to those obtained from the function estimated without pollutant outputs. An average value of 1.27 was obtained for RTS. Compared to returns to scale estimates from previous studies, the estimates obtained here are lower and are, arguably, more defensible. The estimated value from Sherif (1983) is 1.5. Martinello (1985) and Frank et al. (1990) report returns to scale estimates of 2.0 and 1.79, respectively.

The average level of productive efficiency for the period was estimated to be 99.6 percent. The productive efficiency estimates were less than 100 percent for 1967, 1968, 1974, 1976, 1979, 1982, 1986 and 1989. At 96.2 percent, 1976 was the year with the least productive efficiency, followed by 1989 at 96.5 percent level of efficiency.

Productivity growth estimates, however, change dramatically when pollutant outputs are incorporated into the analysis. The average annual growth rate of the Malmquist index obtained from the input distance function that includes undesirable outputs is 1.00 percent. This estimate is substantially higher than the rate of 0.19 percent calculated from the input distance function involving no pollutant outputs. The results also show that most of the productivity growth in the Canadian pulp and paper industry occurred in the period after 1982 and was fastest in the first half of the 1990s. Mean productivity growth estimates of −0.12, −0.32, 1.84 and 4.19 were obtained for the 1959–1969, 1970–79, 1980–89 and 1990–94 periods, respectively. See Table 1 for the complete efficiency and productivity growth estimates.

The productivity indexes from the input distance function with and without undesirable outputs are plotted in the chart in Figure 1. Productivity measured in environmentally sensitive ways is higher than the conventional measure of productivity throughout the period. According to the conventional measure, the productivity of the Canadian pulp and paper industry increased by only 7 per cent over the entire 36 year period from 1959 to 1994. By comparison, the results from the analysis with pollutant outputs indicate that the industry was 41.8 per cent more productive in 1994 than it was in 1959.

Table 1. Shadow Prices, Technical Efficiency and Productivity Growth Estimates from
Input Distance Function Incorporating Pollutant Outputs:
Canadian Pulp and Paper Industry, 1959–1994.

Year	Technical Efficiency	Malmquist Productivity Growth Rate	Malmquist Productivity Index (1959=1.00)	BOD Shadow Prices ($/MT)	TSS Shadow Prices ($/MT)
1959	1.000	-	1.000	$0	$128
1960	1.000	-0.83%	0.992	$26	$85
1961	1.000	0.36%	0.995	$17	$137
1962	1.000	0.03%	0.996	$27	$147
1963	1.000	-0.80%	0.988	$40	$189
1964	1.000	-0.70%	0.981	$24	$145
1965	1.000	-0.15%	0.979	$29	$197
1966	0.998	-0.20%	0.977	$42	$218
1967	0.997	-0.20%	0.976	$48	$254
1968	1.000	0.32%	0.979	$89	$134
1969	1.000	1.00%	0.988	$101	$135
1970	1.000	1.10%	0.999	$42	$76
1971	1.000	-0.32%	0.996	$0	$0
1972	1.000	-1.80%	0.978	$8	$225
1973	1.000	-2.75%	0.952	$0	$88
1974	0.989	-3.15%	0.922	$58	$197
1975	1.000	1.51%	0.936	$25	$282
1976	0.962	-2.16%	0.916	$76	$260
1977	1.000	5.14%	0.965	$76	$247
1978	1.000	0.50%	0.969	$48	$199
1979	0.985	-1.29%	0.957	$13	$0
1980	1.000	0.98%	0.966	$0	$493
1981	1.000	-0.07%	0.966	$63	$802
1982	0.983	-0.90%	0.957	$0	$889
1983	1.000	3.33%	0.990	$151	$261
1984	1.000	3.00%	1.020	$203	$630
1985	1.000	3.80%	1.059	$392	$0
1986	0.985	1.67%	1.077	$217	$0
1987	1.000	3.85%	1.119	$193	$294
1988	1.000	2.87%	1.152	$247	$281
1989	0.965	-0.14%	1.150	$0	$0
1990	1.000	7.18%	1.236	$0	$0
1991	1.000	3.95%	1.285	$554	$501

Table 1. Continued

| Year	Technical Efficiency	Malmquist Productivity Growth Rate	Malmquist Productivity Index (1959=1.00)	BOD Shadow Prices ($/MT)	TSS Shadow Prices ($/MT)
1992	1.000	4.41%	1.343	$1,596	$0
1993	1.000	3.36%	1.389	$30	$0
1994	1.000	2.06%	1.418	$0	$2,814
Averages					
1959–1994	0.996	1.00%	1.044	$123	$286
1959–1969	1.000	-0.12%	0.986	$40	$161
1970–1979	0.994	-0.32%	0.959	$34	$157
1980–1989	0.993	1.84%	1.046	$147	$365
1990–1994	1.000	4.19%	1.334	$436	$663
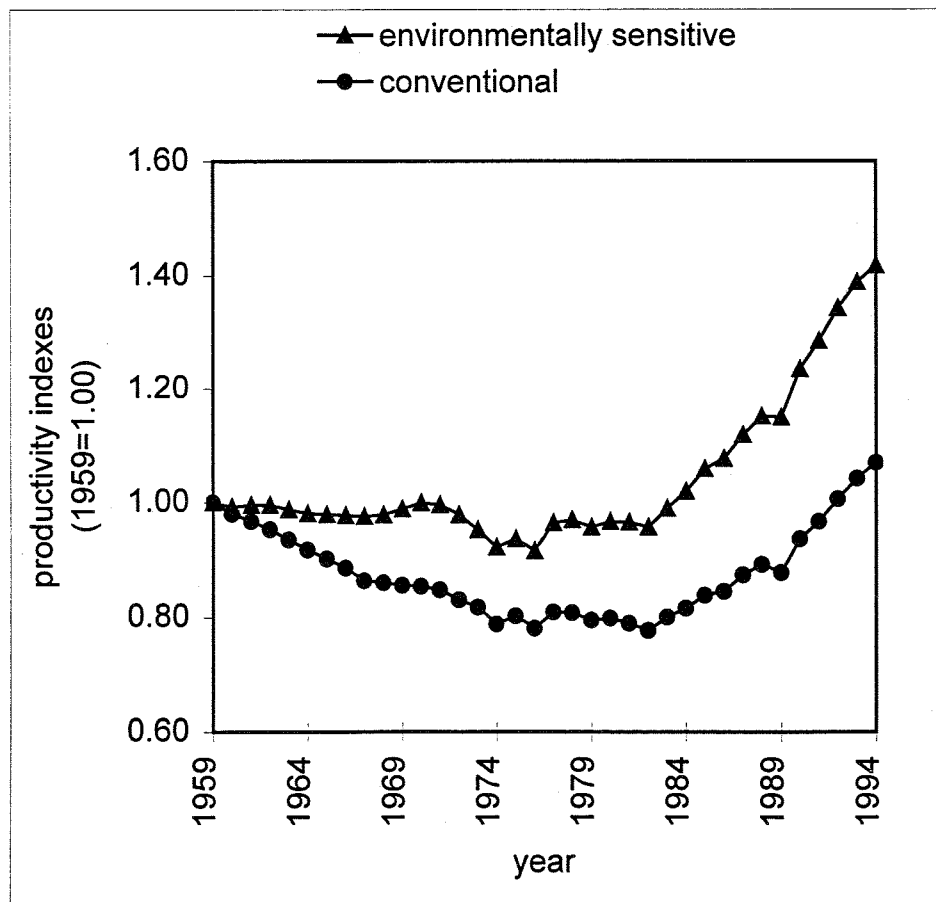
Figure 1. Malmquist Productivity Indexes for the Canadian Pulp and Paper Industry, 1959–1994: Results from Input Distance Functions.

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Abatement Cost (Shadow Price) Estimates for Pollutants

Pollutant shadow prices were calculated using equation [9c]. The market price of paperboards was assumed to be equal to its shadow price. Then the pollutant shadow prices were determined by multiplying the price of paperboards and the ratio of the derivative values of the input distance function with respect to the pollutant and to paperboards. The ratio of these derivatives reflects the tradeoff between the pollutant and paperboard, from the perspective of the producer. The calculated shadow prices measure the cost of pollution abatement to the producer (and also to society). The estimated shadow prices are plotted in Figures 2 and 3.

The calculated shadow prices of Biological Oxygen Demand (BOD) were generally less than $100 for the first two decades covered in this study. The average shadow prices for the 1960s and the 1970s were very close. The prices for the 1980's and the '90s are, however, much higher. The average BOD shadow price increases from $34 for the 1970s to $147 per metric tonne for the 1980's and to $436 per metric tonne for the period from 1990 to 1994. The average value of the BOD shadow prices for the period 1959 to 1994 is $123 per metric tonne.

Shadow prices for Total Suspended Solids were generally found to be higher than shadow price estimates for Biological Oxygen Demand. For the period from 1959 to 1994, the average of the TSS shadow prices was calculated to be $286 per metric tonne. Like the BOD prices, the TSS prices show increasing trends over time. TSS shadow price estimates ranged between $100 and $300 during the 1960s and 1970s with average values of $161 and $157 per metric tonne, respectively. Average prices of $365 and $663 per metric tonne of TSS were calculated for the 1980 to 1989 and 1990 to 1994 periods, respectively.

SUMMARY AND CONCLUSION

This study attempted to analyze productivity trends in the Canadian pulp and paper industry in a way that is sensitive to the environmental effects of the industry's production activity. This was done by estimating a parametric input distance function frontier that incorporates both desirable and undesirable outputs. The parameters of the function were estimated using mathematical
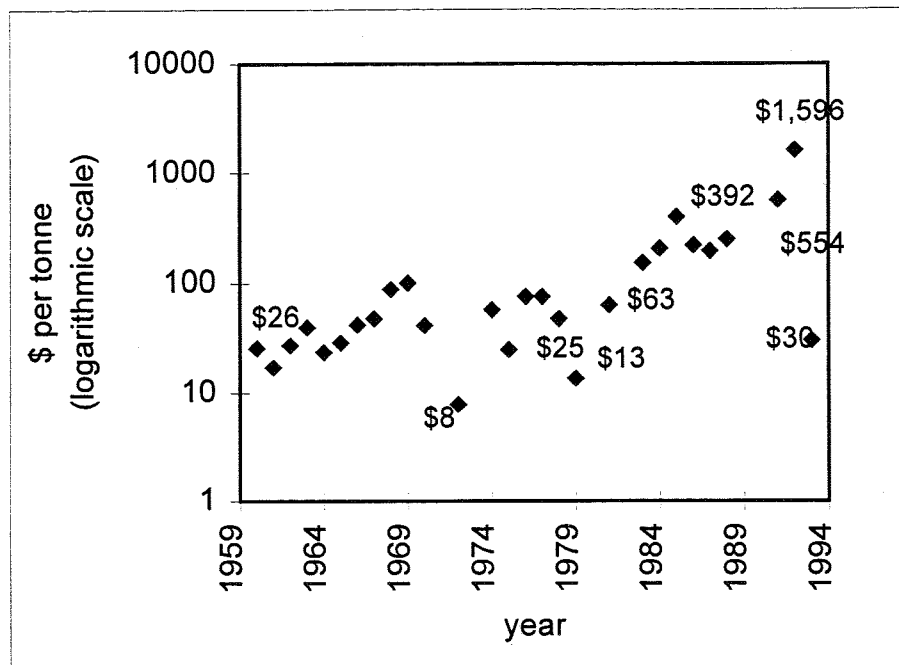
Figure 2. Biological Oxygen Demand (BOD) Abatement Cost (or Shadow Price) Estimates Derived from Input Distance Function: Canadian Pulp and Paper Industry, 1959-1994.
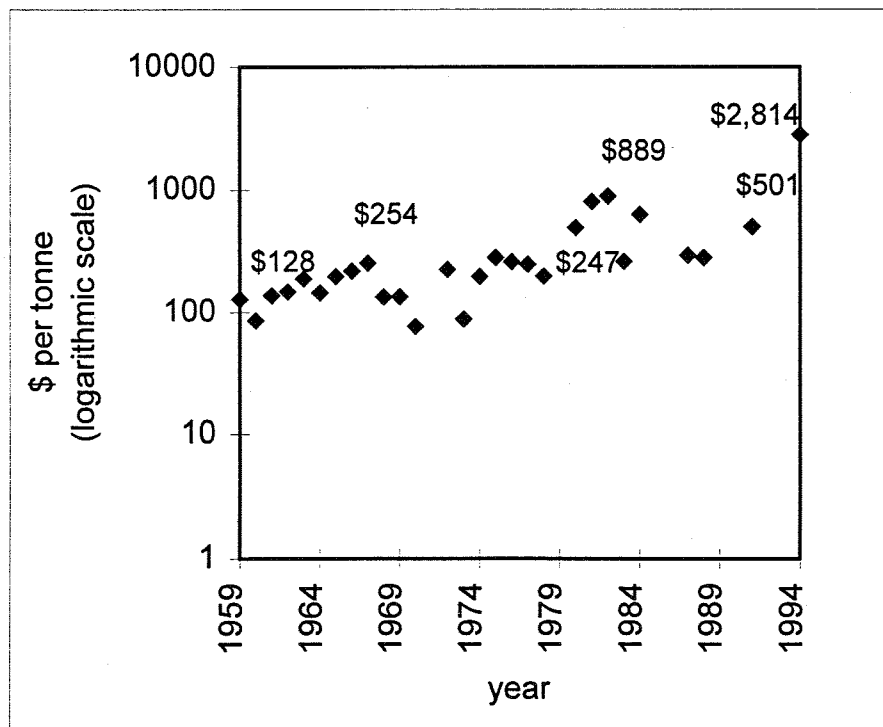

Figure 3. Total Suspended Solids (TSS) Abatement Cost (or Shadow Price) Estimates Derived from Input Distance Function: The Canadian Pulp and Paper Industry, 1959-1994.

programming. Data covering the period from 1959 to 1994 are used. Four desirable outputs, two major water pollutant outputs (BOD and TSS) and seven inputs were identified for the estimation of the input distance function.

The degree of productive or technical efficiency was found to be high during most of the periods. This is not surprising, given the nature of the data (a single time series) and the objective function (minimizing the sum of deviations from the frontier) in the parameter estimation procedure. If instead, panel data were used, efficiency level estimates would then be computed by comparing different observations from the same period as well as different periods. The greater the number of observations that a given observation is compared to, the lower the efficiency estimate for that observation is likely to be.

Nonetheless, many of the periods identified as inefficient in our estimation coincide with oil crises and macroeconomic recession periods. In terms of generating information on efficiency changes, that probably is as good as the results can be because of the data features just discussed.

The results also indicate that the production technology of the industry is characterized by increasing returns to scale. This confirms evidence from previous studies on the industry. Our average returns to scale estimate was 1.27, from both the input distance functions with and without pollutant outputs. This estimate is lower than those reported in several previous studies.

The technical change estimates indicate that productivity measures that ignore pollutant outputs substantially underestimate the performance of the industry. Our environmentally sensitive approach indicates that the total factor productivity of the industry has been growing at the rate of 1.00 percent per year over the period from 1959 to 1994. This is higher than most of the productivity growth estimates obtained for the industry, regardless of whether those estimates include output scale effects as well as technical change and efficiency improvement. This estimate is also considerably higher than the estimate of 0.19 percent per year that we obtained from the input distance function estimated without pollutant outputs. The main conclusion of this study is that productivity improvement, from the social viewpoint, has been stronger than conventional measures

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would suggest. Our shadow price estimates, however, indicate that the cost to producers of pollution control has been rising.

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