Alternative methods for environmentally adjusted productivity analysis

Atakelty Hailu*, Terrence S. Veeman

Department of Rural Economy, University of Alberta, Edmonton AB, Canada T6G-2H1

Abstract

Advances in the productivity with which food is produced around the world have been made possible through the intensive use of industrial inputs that have important environmental impacts. Like standard measures of macroeconomic performance, however, commonly used measures of agricultural efficiency and productivity account only for marketed commodities and inputs, but ignore the environmental effects of these production processes. A more complete analysis of trends in the sector's productivity requires the use of models that incorporate these environmental effects to provide better measures of the contributions of the sector from the social point of view. This paper compares the conceptual merits and empirical performance of alternative approaches that can be employed for this purpose: input distance functions, output distance functions, nonparametric methods, and index number approaches. Each of the methods has relative strengths and weaknesses. The methods are empirically illustrated using data from the Canadian pulp and paper industry. © 2001 Elsevier Science B.V. All rights reserved.

JEL classification: D24; L73; O47; Q25

Keywords: Environmentally adjusted productivity measurement; Input distance functions; Output distance functions; Malmquist indices; Nonparametric analysis; Tornqvist indices

1. Introduction

While the need for adjusting national income accounts for natural resource depletion has been long recognized, relatively little has been done in the productivity literature to incorporate environmental effects into conventional measures of plant, firm or industry economic performance. Conventional measures of efficiency and productivity account for marketed outputs and inputs, but ignore changes in by-products or undesirable outputs. Such uneven treatment of marketed commodities and pollutant outputs leads to distortions in our assessment of productivity changes, especially in industries such as agriculture or pulp and paper where progress is based on production processes that have significant environmental effects. Ball et al. (1994), for example, estimate productivity growth in US agriculture to be 12–28% lower than conventional measures indicate if pollution due to excess nitrogen is taken into account. This paper reviews the merits and demerits of the alternative approaches to environmentally adjusted analysis that can be applied to agriculture, and illustrates their actual empirical application in the case of the Canadian pulp and paper industry.

2. Alternative approaches

Some attempts have been made in the literature to incorporate pollutant outputs in efficiency and pro-

* Corresponding author. Tel.: +1-780-492-1518;
fax: +1-780-492-0268.
E-mail address: atakelty.hailu@ualberta.ca (A. Hailu).

ductivity analysis. The analytical tools employed fall into three broad categories: index number, parametric and nonparametric. The parametric approaches have mainly involved output distance function (e.g. Fare et al., 1993; Coggins and Swinton, 1996) or input distance function (e.g. Hailu, 1998; Hailu and Veeman, 2000) representations of multi-output production technologies. Most nonparametric approaches are based on the data envelopment analysis (DEA) model. These alternative methods are briefly discussed and compared below.

2.1. Index number methods

Pittman (1983) provided the earliest attempt at incorporating undesirable outputs in efficiency measurement. He computed enhanced Caves et al. (1982a) multilateral productivity indices to compare the productive efficiencies of a sample of 30 pulp and paper mills in Wisconsin. Shadow prices for water and airborne effluents from mills were used in the calculation of the indices. For airborne effluents, Pittman calculated the shadow prices based on expenditure on pollution abatement data collected through a 1976 survey conducted by the US Bureau of the Census. Two alternative sets of shadow price estimates were used for water effluents. The first set covers only biological oxygen demand (BOD) and is based on Pittman's previous econometric estimation of shadow prices for the sample of mills used in his study. The second set of shadow prices is obtained from 1977 US Environmental Protection Agency national engineering estimates of the marginal cost of waterborne effluent reduction. Pittman concludes that while interplant differences in productivity are not explained by the failure to include undesirable outputs in traditional measures, the inclusion of undesirable outputs does result in substantial changes in the productivity rankings of plants where undesirable outputs are important.

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 indices for three US industries, namely, agriculture, electric power and pulp and paper. Snapshots of damage value estimates are used to generate two time series of damage values. The first series assumes that the damage values stayed constant through the period. For the second series, damage values are assumed to have changed proportionally with GDP. The study finds that the conventional productivity growth estimates were lower than the adjusted estimates in all three industries. For US agriculture, the average annual productivity growth rate was 2.30% according to the conventional measure. However, when even only soil erosion damages are taken into account, the average rate is estimated to be 2.38 and 2.41%, depending on whether damage values are assumed to be proportional to GDP or to remain constant over time.

The advantage of the index number approach is that it does not involve the estimation of parameters. As a result, the index number approach is not constrained by degrees of freedom requirements and can be applied as long as there are two or more observations to be compared. This advantage is likely to be very useful in cases where there is only a short time series data set including undesirable outputs. However, the index method has disadvantages. First, it requires not only quantity data but also data on the prices of all inputs and outputs included in the calculation. The price data requirement can be a problem especially in the case of non-marketed outputs or inputs. Index number approaches also depend on external damage value estimates (as in Repetto et al., 1996) or on the estimation of pollutant shadow prices, either from a survey of abatement expenditures (e.g. Pittman, 1983) or from a separate analysis of the production technology (e.g. Pittman, 1983; Ball et al., 1994). Gathering data on actual abatement expenditures through surveys 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 difficult to obtain, and damage values often have to be approximated through extrapolation over time and space to generate adjusted productivity growth estimates.

Second, the index number approach does not allow us to identify productivity growth components that have different managerial and policy implications. For example, we cannot distinguish between sources of productivity change that should be attributed to technical change, changes in the degree of technical efficiency, and changes in the scale of production.

2.2. Distance function methods

The use of parametric output and input distance functions incorporating both desirable and undesirable outputs can help overcome some of the data problems associated with the index number approaches discussed above. Both input and output distance functions are capable of handling multi-output technologies and both require only quantity data on inputs and outputs (Shephard, 1970; Fare and Primont, 1995). In fact, shadow prices or marginal cost of abatement estimates for undesirable outputs can be computed from the distance functions. The function values in both cases provide commonly used Farrell measures of technical efficiency. Unlike cost or profit function approaches, distance function approaches can be used to measure total factor productivity without adopting behavioral assumptions about the producer. Finally, the distance function approach also provides an estimated parametric representation of the technology that can be used in further analysis. Marginal costs of pollution abatement (or shadow prices of undesirable outputs) can be computed based on the tradeoff between pollution abatement and desirable outputs implied by the estimated distance function.

2.2.1. Input distance functions

The input distance function measures the maximum proportion by which the input vector can be deflated, given the vector of outputs and the state of the technology. For the case of a production technology using N inputs to produce M desirable and undesirable outputs, the input distance function, $\Psi(u, x, t)$, is technically defined as follows (Shephard, 1970; Fare and Primont, 1995):

$$\Psi(u, x, t) = \max_\theta \left\{ \theta : \left(u, \frac{x}{\theta} \right) \in Y(t), \theta \in R_+ \right\} \quad (1)$$

where x and u are the input and the output vectors, respectively, t the time trend variable, $Y(t)$ the production possibility set at time t, and θ is a scalar on the non-negative segment of the real line (or R_+). Thus, by definition, the reciprocal of the value of the input distance function provides an input-based Farrell measure of technical efficiency (TE_x). A value greater than one for the input distance function indicates that the observed input–output vector is technically ineffi-

cient. When the producer is operating on the technically efficient frontier or the isoquant, the input distance function attains a value of one. An input-based measure of technical change (TC_x) can be obtained by taking the derivative of the input distance function with respect to time ($\partial \Psi / \partial t$). The returns to scale (RTS) value measures the proportion by which the output vector expands given a proportional change in the input vector and can be technically defined as follows for the input distance function (see Fare and Primont, 1995):

$$RTS = [-\nabla_u \Psi(\cdot) u]^{-1} \quad (2)$$

The input distance function has the following properties: it is a non-decreasing and continuous function of x for a non-negative vector of outputs u; it is concave and homogeneous of degree one in x; and it is an upper semi-continuous and quasi-concave function of u (Shephard, 1970, p. 207). The input distance function is non-increasing in desirable outputs and non-decreasing in inputs and undesirable outputs (Hailu and Veeman, 2000).

The following input-based Malmquist productivity index due to Caves et al. (1982a) can be computed from the input distance function results:

$$\begin{aligned}
\ln & M(x^{t+1}, x^t, u^{t+1}, u^t) \\
&= [\ln TE_x(u^{t+1}, x^{t+1}, t+1) - \ln TE_x(u^t, x^t, t)] \\
&\quad + \tfrac{1}{2}[TC_x(u^{t+1}, x^{t+1}, t+1) + TC_x(u^t, x^t, t)]
\end{aligned} \quad (3)$$

The first term in square brackets measures the rate of improvement in the degree of 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 $t + 1$. The index measures productivity change due to technical efficiency improvement and technical change, but excludes the effects of output scale changes.

The above Malmquist index is related to the commonly used Tornqvist productivity index. Caves et al. (1982b) show that the Malmquist input-based productivity index, M, can be rewritten as

follows:

$$\ln M(x^{t+1}, x^t, u^{t+1}, u^t)$$

$$=(0.5)\sum_{m=1}^{4}\left[\left(\frac{r_m^{t+1}u_m^{t+1}}{r^{t+1}u^{t+1}}+\frac{r_m^t u_m^t}{r^t u^t}\right)(\ln u_m^{t+1}-\ln u_m^t)\right]$$

$$-(0.5)\sum_{n=1}^{7}\left[\left(\frac{p_n^{t+1}x_n^{t+1}}{p^{t+1}x^{t+1}}+\frac{p_n^t x_n^t}{p^t x^t}\right)(\ln x_n^{t+1}-\ln x_n^t)\right]$$

$$+(0.5)\sum_{m=1}^{4}\left\{\left[\left(\frac{1}{\varepsilon^{t+1}}-1\right)\left(\frac{r_m^{t+1}u_m^{t+1}}{r^{t+1}u^{t+1}}\right)+\left(\frac{1}{\varepsilon^t}-1\right)\right.\right.$$

$$\left.\left.\times\left(\frac{r_m^t u_m^t}{r^t u^t}\right)(\ln u_m^{t+1}-\ln u_m^t)\right]\right\} \qquad (4)$$

where r and p denote output and input price vectors, respectively, and ε^{t+1} and ε^t are the RTS values for periods $t+1$ and t, respectively. The first two terms on the RHS of Eq. (4) are equal to the Tornqvist index for comparing productivity in period $t+1$ with that in period t. The third term represents the scale factor that constitutes the difference between the Malmquist and Tornqvist indices. This relationship is used to derive a Malmquist index from the Tornqvist formula by removing scale effects from the latter.

2.2.2. Output distance functions

The output distance function, $\Omega(x, u, t)$, measures the minimum amount by which the output vector u can be deflated, given the input vector x (Shephard, 1970; Fare and Primont, 1995), i.e.

$$\Omega(x, u, t) = \min_{\delta}\left\{\delta : \left(x, \frac{u}{\delta}\right) \in Y(t), \delta \in R_+\right\} \qquad (5)$$

It measures the maximum proportional expansion of the output vector that can be achieved given the input vector and the state of technology. The value of the output distance function directly provides an output-based Farrell measure of technical efficiency (TE$_u$). When the observed input–output vector is technically inefficient, the value of $\Omega(\cdot)$ is less than one. The negative of the derivative of the function with respect to time provides an output-based measure of technical change. The measure of RTS is provided by

$$\text{RTS} = -\nabla_x \Omega(\cdot)x \qquad (6)$$

The input-based measures of technical efficiency and technical change can be obtained from the output

distance function as follows: [1]

$$\text{TE}_x = 1 - \frac{\Omega^{-1} - 1}{\text{RTS}} \qquad (7)$$

$$\text{TC}_x = \frac{-(\partial\Omega/\partial t)}{\text{RTS}} \qquad (8)$$

The output distance function has the following properties: it is a non-increasing function of x for $u \in R_+^M$; it is continuous, convex and homogeneous of degree one in u; and it is a lower semi-continuous and quasi-convex function of x (Shephard, 1970, p. 208). The function is specified to be non-decreasing in desirable outputs but non-increasing in inputs and undesirable outputs (Fare et al., 1993).

2.3. Nonparametric methods

Unlike their index number and parametric alternatives, nonparametric methods have the advantage of imposing no a priori restrictions on the functional form of the underlying technology. The nonparametric models employed in the literature on environmental performance measurement are typically based on the DEA model (e.g. Fare et al., 1989; Ball et al., 1994; Shaik and Perrin, 1999).

Hailu and Veeman (2001a) propose the combined use of inner bound (DEA) and outer bound nonparametric representations that incorporate undesirable outputs based on modifications to the Varian–Banker–Maindiratta (Banker and Maindiratta, 1988; Varian, 1984) nonparametric models as extended by Chavas and Cox (1997) into the analysis of technical change. These inner and outer nonparametric bounds (EYI^e and EYO^e, respectively) are represented by the following two sets:

$$\text{EYI}^e = \left\{(v, w, x)\left| v \le \sum_{t \in T} z^t V^t, w \ge \sum_{t \in T} z^t W^t, x\right.\right.$$

$$\left.\ge \sum_{t \in T} z^t X^t, \sum_{t \in T} z^t = 1; v, w, x, z^t \ge 0; ^t \in T\right\} \qquad (9)$$

$$\text{EYO}^e = \{(v, w, x)|r^t v + q^t w - p^t x \le r^t V^t$$

$$+ q^t W^t - p^t X^t; t \in E; v, w, x \ge 0\} \qquad (10)$$

---

[1] These derivations are based on the translation of output changes to input changes using the returns to scale factor.

where v and p now denote the quantity and price vectors of desirable outputs, w and q the undesirable output quantity and (shadow) price vectors, respectively, V^t, W^t, and X^t the vectors of effective quantities of desirable outputs, undesirable outputs and inputs for observation t computed from actual quantities using the Chavas and Cox (1997) 'augmentation hypothesis', respectively, and z^t is the intensity variable assigned to observation t in the construction of the effective technology frontier.

The 'effective quantities' are obtained by modifying actual quantities using technology indices. Following Chavas and Cox, we adopt a translation hypothesis for the relationship between effective and actual inputs, i.e.

$$X_n^t = x_n^t - A_n^t; \qquad V_m^t = v_m^t + B_m^t;$$
$$W_k^t = w_k^t - C_k^t \qquad (11)$$

The technology indices (A, B, C) represent the minimum perturbation to the sample of observations required to satisfy Varian's weak axiom of profit maximization (WAPM) at all data points. We computed the technology indices by minimizing the sum of the ratios of these indices to actual quantity values, subject to the following conditions: (1) all technology indices and all effective quantities are non-negative (Eq. (14)); and (2) all the observations satisfy the WAPM test in effective quantities (Eq. (13)). The first condition ensures that all actual sample observations are elements of the 'effective technology', i.e. $x_n^t \geq X_n^t$, $v_m^t \leq V_m^t$, and $w_k^t \geq W_k^t$. It also rules out non-positive input and output quantities as elements of the constructed technology. The second constraint ensures that the outer bound is constructed out of all the observations expressed in effective quantities. The linear programming problem for computing the technology indices is summarized in Eqs. (12)–(14):

$$\min_{A,B,C} \sum_{t \in T} \left\{ \sum_n \frac{A_n^t}{x_n^t} + \sum_m \frac{B_m^t}{v_m^t} + \sum_k \frac{C_k^t}{w_k^t} \right\} \qquad (12)$$

subject to

$$r^t V^s + q^t W^s - p^t X^s \leq r^t V^t + q^t W^t - p^t X^t \qquad (13)$$

and

$$A, B, C, V, W, X \geq 0; \quad s, t \in T \qquad (14)$$

The intertemporal nonparametric bounds in Eqs. (9) and (10) are used to compute productivity indices for the inner and outer bound representations, respectively. Additional details on the computation of these productivity indices are provided in Hailu and Veeman (2001a).

3. Empirical estimates

The alternative methods discussed above are empirically compared using Canadian pulp and paper industry time series data for the period from 1959 to 1994. This industry was chosen for two reasons. First, sufficient data is available on pollutant outputs from this industry to make possible the implementation of all the methods outlined in Section 2. Second, the Canadian pulp and paper industry has achieved substantial progress in pollution abatement and thus provides an excellent case for illustrating the extent to which conventional measures of productivity change can diverge from environmentally adjusted ones. The output data for this industry include four desirable outputs (i.e. newsprint, other paper, paperboards, and net wood pulp output) and two undesirable outputs (i.e. BOD and total suspended solids (TSS)). Seven production inputs (i.e. energy, wood residue, pulpwood, non-wood materials, production labor, administration labor, and capital) are included in the study.

The flexible translog functional form was adopted for the distance functions and the parameters were estimated using mathematical (goal) programming methods. This estimation method relies on the minimization of the sum of deviations of the values of the function from the unknown frontier that is being estimated, subject to the appropriate monotonicity, homogeneity and translog symmetry conditions.[2]

Input-based measures of productivity change are used for three major reasons: (1) unlike the traditional output-based measure, the input-based measure remains meaningful even in the presence of undesirable outputs; (2) unlike recently proposed hyperbolic output-based measures (e.g. Fare et al., 1989), the input-based measure has a straightforward interpretation in terms of cost saving; and (3) the input-based

---

[2] See Fare et al. (1993), Hailu (1998) or Hailu and Veeman (2000) for more details on the estimation procedures.

measure appropriately credits the producer not only for increases in desirable outputs but also for reduction in undesirable outputs or for pollution abatement.

Returns to scale and input-based measures of productivity change were derived from the estimated distance functions. BOD and TSS shadow prices derived from the input distance function (Hailu and Veeman, 2000) were used as pollutant output prices in the construction of the index number and outer bound nonparametric productivity series. The RTS estimates obtained from the input distance function were also used to derive Malmquist productivity indices from the Tornqvist productivity index formula by removing output scale effects from the latter (see Eq. (4)). The results of these different methods are briefly discussed below.

The results from both the input and output distance function approaches indicate high overall levels of technical efficiency[3] and that the production technology is characterized by moderately increasing RTS.[4] The shadow price estimates also clearly indicate that the cost of pollution abatement has been rising for both BOD and TSS.

The following important points should be noted about the productivity growth estimates (see Table 1). First, productivity estimates as measured by commonly used index number approaches mainly reflect the effects of output scale effects. For the conventional approach, for example, the average productivity growth obtained from the Tornqvist index is 0.41% per year. When this is adjusted for output scale effects, we find that productivity growth (due to technical efficiency change and technical change) occurred at an average rate of 0.15%. Second, conventional measures consistently provide productivity growth estimates below those obtained when pollutant outputs are incorporated into the analysis. In

Table 1
Summary of average annual productivity growth estimates (%)

Productivity measure	Conventional	Environmentally adjusted
Tornqvist index	0.41	0.79
Malmquist index based on Tornqvist index	−0.15	0.25
Malmquist index based on input distance function	0.19	1.00
Malmquist index based on output distance function	−0.37	0.67
Nonparametric analysis in effective quantities	1.80	2.10

the case of the input and output distance function results, for example, conventional estimates understate the true rate of average annual productivity growth by at least 0.81%. The conventional and environmentally adjusted productivity indices for the Canadian pulp and paper industry are shown in Fig. 1. In this industry, environmentally adjusted indices are consistently higher than conventional indices. In industries where pollution problems have been getting worse, however, environmentally adjusted indices would be lower than their conventional counterparts.

Finally, we find a large gap between the productivity growth estimates obtained from the inner and outer bound nonparametric representations shown in Eqs. (9) and (10). The estimates from the inner bound

---

[3] About 96 and 99% for the input and output distance functions, respectively, both with and without the inclusion of pollutant outputs. These high estimates of the degree of technical efficiency are partly due to the nature of the data used, i.e. time series data on a single producer or industry. The use of panel data would have allowed for a better discrimination among the different data points. Subsequent research conducted by the authors (Hailu and Veeman, 2001b) using regional level panel data indicates the presence of substantial technical efficiency differentials.

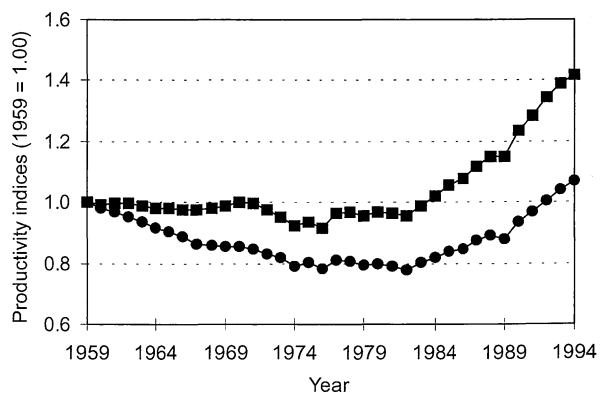[4] The average RTS estimates range from 1.14 to 1.27.

Fig. 1. Malmquist productivity indexes for the Canadian pulp and paper industry based on input distance functions: (■) environmentally adjusted; (●) conventional.

(DEA) nonparametric approach indicate zero productivity growth, with or without the inclusion of undesirable outputs. This is to be expected because EYI^e is based on the construction of the smallest convex hull that includes the observed input-output combinations and as such discriminates the least among the observations. The outer bound nonparametric frontier (EYO^e), on the other hand, includes all admissible technologies that could have generated the data. As a result, the calculations based on EYO^e indicate substantial improvement in productivity. The calculated average annual rates from EYO^e are 3.9 and 4.5% for the conventional and environmentally adjusted representations, respectively. Similar gaps between inner and outer bound results have been observed by other researchers (e.g. Chavas and Cox, 1997) using these methods. Since the estimates from the inner and outer nonparametric bounds provide, respectively, lower and upper bounds for the true but unknown productivity growth rates, we use the geometric means of the resulting productivity scores to approximate the actual productivity growth rates. The estimates based on these averages are reported in the last row of Table 1 and indicate that average annual environmentally adjusted productivity growth is 0.3% points higher than conventional growth.

The gaps between conventional and environmentally adjusted estimates identified by the different approaches indicate the extent to which conventional measures can distort our understanding of the degree of economic performance. The Canadian pulp and paper industry has spent large sums of money to reduce pollution output. As a result, BOD and TSS rates have declined from 102 and 118 kg/t of wood pulp produced to only 13 and 6 kg/t, respectively, in the period between 1959 and 1994. Total industry outputs of these pollutants have fallen by 68 and 87.2%, respectively, over this same period while the aggregate quantity of desirable outputs has increased by 220%.

By ignoring these changes in pollutant outputs, conventional measures fail to recognize the fact that a higher percentage of inputs could have been saved if there had been no pollution abatement. The environmentally adjusted estimates, on the other hand, measure the input saving that could have been achieved if outputs (including undesirable) had been held constant.

4. Conclusion

In the last decade, there has been a growing research interest in the use of measures of efficiency and productivity change that take environmental effects into account. A major shortcoming of conventional measures of economic performance is the fact that they account for marketed outputs, but ignore changes in the environmental impacts of economic activity.

This paper compared the conceptual merits and empirical performance of index number, input distance function, output distance function, and inner (DEA) and outer bound nonparametric approaches to the environmentally adjusted analysis of productivity performance. The index number and the outer bound nonparametric approaches require estimates of the costs of pollution abatement that have to be obtained from other studies. Estimates based on the inner and outer bound nonparametric approaches provide, respectively, lower and upper bounds for the true but unknown productivity growth rates, leading to large gaps in the results obtained. The distance function approaches appear to be most promising for the following reasons. First, these approaches require only quantity data. Second, estimates of the cost of pollution abatement can be readily obtained from these methods. Third, when flexible functional forms are employed, input and output distance functions can provide good representations of the underlying technology. Fourth, different components of productivity growth (change in the degree of technical efficiency, technical change, and scale effects) can be easily identified from estimated distance functions.

The results from all the approaches consistently show that conventional measures of productivity growth that ignore pollutant outputs underestimate productivity improvements in the Canadian pulp and paper industry by failing to credit the industry for its production of improved environmental quality through pollution abatement. While the direction of the adjustment in the case of agriculture is likely to depend on trends in agriculture's management of the environment over a given period, the results we obtained for the Canadian pulp and paper industry clearly suggest that adjusting agricultural productivity measures for environmental effects would significantly improve our understanding of productivity change in agriculture.

Acknowledgements

References

Ball, V.E., Lovell, C.A.K., Nehring, R., Somwaru, A., 1994. Incorporating undesirable outputs into models of production: an application to US agriculture. Cahiers d'Economie et Sociologie Rurales 31, 60–74.

Banker, R.D., Maindiratta, A., 1988. Nonparametric analysis of technical and allocative efficiencies in production. Econometrica 56, 1315–1332.

Caves, D.W., Christensen, L.R., Diewert, W.E., 1982a. Multilateral comparisons of output, input, and productivity using superlative index numbers. Econ. J. 92, 73–86.

Caves, D.W., Christensen, L.R., Diewert, W.E., 1982b. The economic theory of index numbers and the measurement of input, output and productivity. Econometrica 50, 1393–1414.

Chavas, J.P., Cox, T.L., 1997. Production analysis: a nonparametric time series application to US agriculture. J. Agric. Econ. 48, 330–348.

Coggins, J.S., Swinton, J.R., 1996. The price of pollution: a dual approach to valuing SO_2 allowances. J. Environ. Econ. Manage. 30, 58–72.

Fare, R., Primont, D., 1995. Multi-Output Production and Duality: Theory and Applications. Kluwer Academic Publishers, Boston.

Fare, R., Grosskopf, S., Lovell, C.A.K., Pasurka, C., 1989. Multilateral productivity comparisons when some outputs are undesirable: a nonparametric approach. Rev. Econ. Stat. 71, 90–98.

Fare, R., Grosskopf, S., Lovell, C.A.K., Yaisawarng, S., 1993. Derivation of shadow prices for undesirable outputs: a distance function approach. Rev. Econ. Stat. 75, 374–380.

Hailu, A., 1998. Environmentally sensitive analysis of economic performance: productivity and efficiency in the Canadian pulp and paper industry, 1959–1994. Ph.D. dissertation, University of Alberta, Edmonton, Canada.

Hailu, A., Veeman, T.S., 2000. Environmentally sensitive productivity analysis of the Canadian pulp and paper industry, 1959–1994: an input distance function approach. J. Environ. Econ. Manage. 40, 251–274.

Hailu, A., Veeman, T.S., 2001a. Nonparametric productivity analysis with undesirable outputs: an application to the Canadian pulp and paper industry. Am. J. Agric. Econ. 83, 605–616.

Hailu, A., Veeman, T.S., 2001b. Pollution abatement and productivity performance of regional Canadian pulp and paper industries. Paper to be presented at the Canadian Agricultural Economics Society and American Agricultural Economics Association Joint Annual Meetings, Chicago, IL, 5–8 August 2001.

Pittman, R.W., 1983. Multilateral comparisons with undesirable outputs. Econ. J. 93, 883–891.

Repetto, R., Rothman, D., Faeth, P., Austin, D., 1996. Has environmental protection really reduced productivity growth? World Resources Institute, Washington, DC.

Shaik, S., Perrin, R., 1999. The role of nonparametric approaches in adjusting productivity measures for environmental impacts. Selected paper AAEA, Nashville, 8–11 August.

Shephard, R.W., 1970. Theory of Cost and Production Functions. Princeton University Press, Princeton, NJ.

Varian, H.R., 1984. The nonparametric approach to production analysis. Econometrica 52, 579–597.