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Direct and Indirect Shadow Price and Cost Estimates of Nitrogen Pollution Abatement

Saleem Shaik
Mississippi State University

Glenn A. Helmers
University of Nebraska - Lincoln, ghelmers1@unl.edu

Michael R. Langemeier
Kansas State University

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Saleem Shaik, Glenn A. Helmers, and Michael R. Langemeier

The implication of treating environmental pollution as an undesirable output (weak disposability) as well as a normal input (strong disposability) on the direct and indirect shadow price and cost estimates of nitrogen pollution abatement is analyzed using Nebraska agriculture sector data. The shadow price of nitrogen pollution abatement treated as an undesirable output represents the reduced revenue from reducing nitrogen pollution. In contrast, the shadow price of nitrogen pollution abatement treated as an input reflects the increased cost of reducing nitrogen pollution. For the 1936–97 period, the estimated shadow price and cost of nitrogen pollution abatement for Nebraska ranges from $0.91 to $2.21 per pound and from $300 to $729 million, respectively.

Key words: direct and indirect approaches, disposability, nitrogen pollution, nonparametric programming, shadow price

Introduction

The short- and long-term effects of agricultural production gains on the environment make it critical for policy makers and economists to be able to assign benefits and costs to environmental pollution. Agriculture, one of the most successful sectors in terms of productivity growth, has outdistanced the rapid growth in demand for its output for the past few decades. This trend has provided large social benefits, such as increased food and fiber products. Yet agriculture has detrimental social effects on the natural environment by generating pollutants. Apart from the increased output and lower price to consumers, the increased use of chemicals (nutrients and pesticides) in agriculture is associated with hidden costs due to environmental pollution. To the extent that unpriced natural resource degradation is a result of agricultural production, the traditional measure of technological advances in agriculture is an overrepresentation of its true value to society.

A number of studies (e.g., Crandall; Gollop and Roberts; Conrad and Morrison; Jorgenson and Wilcoxen) have examined the impact of regulation of environmental pollution on productivity in the nonfarm sector, with studies by both Gardner and Bromley directed toward agriculture. Other studies (see Fare et al. 1989; Yaisawarng and Klein; Coggins and Swinton) using linear programming and a duality framework have made considerable progress in modifying productivity measures for environmental pollution.

Saleem Shaik is post-doctoral research associate, Department of Agricultural Economics, Mississippi State University; Glenn A. Helmers is professor, Department of Agricultural Economics, University of Nebraska-Lincoln; and Michael R. Langemeier is professor, Department of Agricultural Economics, Kansas State University. A contribution of the University of Nebraska Agricultural Research Division, Lincoln, Nebraska—Journal Series No. 13854.

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Linear programming techniques with environmental pollution treated as an undesirable output with weak disposability (used in the hyperbolic output-oriented measure by Fare et al. 1993), or as a normal input, have been employed in the computation of environmentally adjusted productivity (Pittman; Shaik) and efficiency measures (Reinhard, Thijssen, and Lovell). The environmental consequences of chemical use, especially nitrogen pollution, on agricultural production/productivity have not been measured until recently (e.g., Smith 1992, 1998; Hrubovcak, LeBlanc, and Eakin; Shaik; Gollop and Swinand; Weaver; Fare and Grosskopf).

In this analysis, we view environmental pollution as being part of the production process. When environmental pollution is internalized into the production process, the price can be recovered using linear programming or parametric techniques; hence it is labeled as a shadow price. The usefulness of retrieving this shadow price is especially important given the cost of nitrogen pollution abatement is typically disassociated from production decisions. This circumstance leads to the use of chemicals above levels that would occur if environmental pollution outcomes were incorporated into producers' decisions.

In addition to computing the potential nitrogen loss to the environment—including atmosphere, surface water, and groundwater—the main contribution of this study is the estimation of the shadow price and cost of nitrogen pollution abatement in agriculture. Specifically, we examine the implications of treating environmental pollution as an undesirable output with weak disposability as well as a normal input with strong disposability on the direct and indirect shadow price estimates. Using data related to one state (Nebraska), estimates are developed for the time period 1936–1997.

Two methods are developed to estimate the shadow price of environmental pollution abatement treated both as an undesirable output and as a normal input. The first method uses the ratio of the dual values of environmental pollution and the desirable output implicit in the piecewise linear programming constraint to recover the direct shadow prices of environmental pollution (Shaik and Perrin). The second method utilizes a two-stage estimation process to recover the indirect shadow prices (Shaik and Helmers). Irrespective of the methodology, the direct and indirect shadow prices are retrieved as the gradient of the linear programming constraint and the first-order conditions of the distance function. The cost of environmental pollution abatement is computed as the product of the shadow price and the amount of environmental pollution.

Theoretical Model

In the agricultural sector, the technology that transforms inputs $(X = (x_1, x_2, ..., x_i) \in \Re_+^I)$ into desirable outputs $(Y_g = (y_{g,1}, y_{g,2}, ..., y_{g,j}) \in \Re_+^J)$ and environmental pollution $(N \in \Re_+)$ can be represented by the weak disposal output set $P_w(X)$ and the strong disposal input set $L(Y_g)$. This equivalency of treating environmental pollution as an undesirable output with weak disposability or as a normal input with strong disposability can be illustrated for a profit-maximizing firm with the implicit function $F(Y_g, N, X) = 0$.[1] Weak disposability refers to the ability to dispose of environmental pollution as an unwanted commodity at a positive private cost. Joint production of the desirable output (Y_g) and environmental

[1] Environmental pollution can also be viewed as a jointly applied input with another input (for example, fertilizer) and strong or weak disposability. Similar to the assumption of joint production of desirable output and environmental pollution in the output distance function, it is also possible to assume joint application of an input along with environmental pollution with either strong or weak disposability from the input distance function framework.

pollution (N) is assumed in the output set. Strong disposability refers to the ability to dispose of environmental pollution with no private cost.[2]

In general, under the assumption of perfect competition, the first-order conditions of the implicit function with respect to its elements are positive and equal to its prices (in our case, the first-order derivatives are equal to the shadow prices of environmental pollution). If environmental pollution is treated as an undesirable output with weak disposability, the firm would conceptually maximize profits with a negative shadow price ($\partial Y_g / \partial N = -p_N$). The negative price reflects the inward bending of the transformation curve or backward bending of the input requirement set. Similarly, the firm would maximize profits with a positive shadow price ($\partial Y_g / \partial X_{|N=X} = w_{N=X}$) of environmental pollution treated as a normal input with strong disposability. The shadow price estimates of environmental pollution treated as an undesirable output or an input can be recovered directly or indirectly.

The direct approach is one method used to estimate the shadow price of environmental pollution in terms of reduced total revenue. This approach is termed the direct method since the dual values (gradients of environmental pollution and the desirable output variable) implicit in the piecewise linear programming constraint are equivalent to the shadow price under perfect competition.

Following Fare et al. (1989, pp. 92–93), a weak disposal reference set satisfying constant returns to scale, strong disposability of desirable outputs, weak disposability of potential nitrogen pollution, and strong disposability of inputs can be defined as:

$$(1) \qquad P_w^T(X) = \{(Y_g, N): X \text{ can produce } (Y_g, N) \text{ in year } T; \\ 0 \le \theta \le 1 \text{ implies } \theta(Y_g, N) \in P_w^T(X),\ N' < N \Rightarrow \theta(Y_g, N') \in P_w^T(X)\},$$

where $P_w^T(X)$ is a weak disposal output set.

The weak disposal output set can be represented by the output distance function, and the nonlinear programming problem used to calculate the output measure can be evaluated for each year t as:

$$(2) \qquad D_o^T(x^t, y_g^t, N^t)^{-1} = \max_{\theta, \mathbf{z}} \{\theta : (x^t, \theta y_g^t, \theta^{-1} N^t) \in P_w^T(x^t)\}$$

or

$$\max_{\theta, \mathbf{z}} \theta \quad \text{s.t.: } \theta y_g^t \le Y_g \mathbf{z} \qquad \text{where } Y_g = (y_g^1, y_g^2, \ldots, y_g^T)$$
$$\theta^{-1} n^t = N\mathbf{z} \qquad N = (n^1, n^2, \ldots, n^T)$$
$$x^t \ge X\mathbf{z} \qquad X = (x^1, x^2, \ldots, x^T).$$
$$\mathbf{z} \ge 0$$

From (2), $\mathbf{z}$ is a $\{T \times 1\}$ vector of intensity variables, with $\mathbf{z} \ge 0$ identifying the constant-return-to-scale boundaries of the reference set, and the equal sign on the second constraint indicates the weak disposability assumption on environmental pollution with a less than (greater than) sign representing the strong disposability of desirable output (input).

[2] The strong disposability assumption reflects a zero cost to overapplying nitrogen fertilizer. This overapplication leads to excess nitrogen pollution. The excess nitrogen pollution represents an added cost.

The nonlinear constraint (θ^{-1}) on nitrogen pollution is linearized into a linear constraint $(2 - \theta)$ following Fare et al. (1989). Let $f(\theta) = \theta^{-1}$, with the first-order Taylor series expansion of $f(\theta)$ being $\theta^{-1} = \theta^{-1} - \theta^{-2}(\theta - 1)$. If θ is approximated around one, then $\theta^{-1} = 1 - 1(\theta - 1) \equiv (2 - \theta)$; thus $N\mathbf{z} = \theta^{-1}n^t$ would be $N\mathbf{z} = (2 - \theta)n^t$. The linear approximation of the nonlinear programming problem in equation (2) is specified as:

$$\text{(3)} \quad D_o^T(x^t, y_g^t, N^t)^{-1} = \max_{\theta,\mathbf{z}} \theta \quad \text{s.t.: } \begin{array}{l} \theta y_g^t \le Y_g \mathbf{z} \\ (2 - \theta)n^t = N\mathbf{z} \\ x^t \ge X\mathbf{z} \\ \mathbf{z} \ge 0 \end{array} \qquad \begin{array}{l} \text{where } Y_g = (y_g^1, y_g^2, \ldots, y_g^T) \\ N = (n^1, n^2, \ldots, n^T) \\ X = (x^1, x^2, \ldots, x^T). \end{array}$$

The variables in (3) are as previously described in equation (2) above.

Following Shaik, the input reference set satisfying constant returns to scale, strong disposability of the aggregate input, and environmental pollution treated as a normal input can be defined as:

$$\text{(4)} \quad L^T(Y_g) = \left\{(X, N)\text{: } Y_g \text{ produced by } (X, N) \text{ in year } T\right\}.$$

This concept can be represented by an input distance function evaluated for each year t as:

$$\text{(5)} \quad D_i^T(y_g^t, x^t, N^t)^{-1} = \min_{\lambda,\mathbf{z}} \left\{\lambda\text{: } (y_g^t, \lambda x^t, \lambda N^t) \in L^T(y_g^t)\right\}$$

or

$$\min_{\lambda,\mathbf{z}} \lambda \quad \text{s.t.: } \begin{array}{l} y_g^t \le Y_g \mathbf{z} \\ \lambda x^t \ge X\mathbf{z} \\ \lambda n^t \ge N\mathbf{z} \\ \mathbf{z} \ge 0 \end{array} \qquad \begin{array}{l} \text{where } Y_g = (y_g^1, y_g^2, \ldots, y_g^T) \\ X = (x^1, x^2, \ldots, x^T) \\ N = (n^1, n^2, \ldots, n^T). \end{array}$$

From (5), $\mathbf{z}$ is a $\{T \times 1\}$ vector of intensity variables, with $\mathbf{z} \ge 0$ identifying the constant-return-to-scale boundaries of the reference set. The greater than sign represents the strong disposability of the aggregate input and environmental pollution. The less than sign represents the strong disposability of desirable output.

The dual values implicit in the piecewise linear programming constraint from equations (3) and (5), equivalent to the shadow price, can be efficiently retrieved. Specifically, the ratios of the dual values from the linear programming constraint of environmental pollution and desirable output or input allow us to compute the direct shadow price in terms of real total revenue (*Revenue/OQI*) or real total cost (*Cost/IQI*), respectively, as:

$$\text{(6)} \quad Output\ SP_N^D = \frac{\tau_{t,N}}{\tau_{t,y_g}} * Revenue/OQI$$

and

$$\text{(7)} \quad Input\ SP_N^D = \frac{\tau_{t,N}}{\tau_{t,x}} * Cost/IQI,$$

where *SP* is the shadow price of environmental pollution, the superscript *D* represents the direct measures, τ denotes the dual values obtained from the output and input linear programming constraints, and *OQI* and *IQI* are aggregate Tornqvist-Theil output and input quantity indices (discussed in the data section).

The indirect approach can also be used to estimate a shadow price. A two-stage approach is adopted in the estimation of the indirect shadow price of environmental pollution by exploiting the duality between the output (input) distance function and revenue (cost). Shephard, and Fare and Primont have established the duality between the output (input) distance function and revenue (cost). We extended it to include environmental pollution treated both as an undesirable output and as a conventional input. The duality between the output distance-revenue function and the input distance-cost function including environmental pollution can be defined as:

(8)
$$R(x^t, p_g^t, p_N^t) = \max_{y_g, y_N} \left\{ (p_g^t y_g^t - p_N^t N^t) : D_o(x^t, y_g^t, N^t) \le 1 \right\}$$
$$D_o(x^t, y_g^t, N^t) = \sup_{p_g, p_N} \left\{ (p_g^t y_g^t - p_N^t N^t) : R(x^t, p_g^t, p_N^t) \le 1 \right\}$$

and

(9)
$$C(y_g^t, w^t, p_N^t) = \min_{x, y_b} \left\{ (w^t x^t + p_b^t N^t) : D_i(y_g^t, x^t, N^t) \ge 1 \right\}$$
$$D_i(y_g^t, x^t, N^t) = \inf_{w, p_b} \left\{ (w^t x^t + p_b^t N^t) : C(y_g^t, w^t, N^t) \ge 1 \right\},$$

where $R(\cdot)$ and $C(\cdot)$ are the revenue and cost functions corresponding to the output and input distance functions (D_o and D_i), respectively. The prices of the desirable output, environmental pollution, and the input are denoted as p_g^t, p_N^t, and w^t, respectively.

In the first stage, the output and input distance function measures are computed for each observation using a piecewise linear programming model imposing both weak and strong disposability assumptions. The distance function measures so obtained are used as dependent variables in the second stage to retrieve the indirect shadow price. Since price is equal to marginal value product under perfect competition, the shadow price of environmental pollution treated as an undesirable output (conventional input) is calculated from the ratio of the output (input) distance function derivatives with respect to the desirable output (input) and environmental pollution.

Further, to convert the derivatives of output (input) distance functions with respect to the output (input) quantity index and nitrogen pollution into a value, we compute the indirect shadow price in terms of real total revenue (real total cost). The ratios of the output and input parametric distance function derivatives are represented as:

(10)
$$Output\ SP_N^{ID} = \frac{\partial D_o / \partial N}{\partial D_o / \partial y_g} * Revenue/OQI$$
$$= \frac{\tau_{t,N}}{\tau_{t,y_g}} * Revenue/OQI$$

and

$$(11) \qquad Input\ SP_N^{ID} = \frac{\partial D_i / \partial N}{\partial D_i / \partial x} * Cost/IQI = \frac{\tau_{t,N}}{\tau_{t,x}} * Cost/IQI,$$

where *SP* is the shadow price of environmental pollution, the superscript *ID* represents the indirect measures, D_o and D_i are the output and input distance functions, τ denotes the dual values, and *OQI* and *IQI* are aggregate Tornqvist-Theil output and input quantity indices. The ratios of the derivatives (slopes) of the output or input distance functions are estimated using the parametric approach.

In order to compute the indirect shadow prices of environmental pollution treated as undesirable output and input from equations (10) and (11), the following parametric output and input distance function regressions are utilized:

$$(12) \qquad D_o = \alpha_0 + \alpha_g Y_g + \alpha_N N + \alpha_x X + \varepsilon$$

and

$$(13) \qquad D_i = \alpha_0 + \alpha_g Y_g + \alpha_N N + \alpha_x X + \varepsilon,$$

where D_o (D_i) is the output (input) distance function computed with environmental pollution treated as an undesirable output (input) with the weak (strong) disposability assumption, Y_g is the desirable output, *N* is environmental pollution, *X* is the aggregate input, and ε is the error term.

Nebraska Output, Input, and Nitrogen Pollution Data[3]

Input and Output Data

Estimated aggregate input and output Tornqvist-Theil quantity indices for the Nebraska agriculture sector for the 1936 through 1997 time period are used in the analysis. The aggregate output Tornqvist-Theil quantity index (OQI) is computed from 22 commodities including food grains, feed crops, vegetable and oil crops, meat animals, poultry, and other livestock including milk, honey, and wool production. Annual data on crop production (yield per acre times total harvested acres for each crop) and livestock quantity estimates (pounds of meat produced) multiplied by prices received by farmers are used in the construction of the aggregate output Tornqvist-Theil quantity index, with 1936 being the base year.

An aggregate Tornqvist-Theil input quantity index (IQI), with 1936 as the base year, is constructed by aggregating farm equipment (includes trucks, autos, tractors, and other agricultural machinery), breeding livestock (cattle, hogs, sheep and lambs, horses, and mules), farm real estate (nonirrigated cropland, irrigated cropland, pasture, and buildings and structures), farm labor, and intermediate inputs.

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[3] This section borrows heavily from chapter 3 of Shaik's dissertation.

Particular emphasis is given to quantity and quality changes in the construction of farm equipment, breeding livestock, farm real estate, farm labor, and intermediate inputs. In the case of farm equipment, a perpetual inventory method is used in the construction of the capital stock for the four assets: trucks, autos, tractors, and other agricultural machinery. Rental values are used to construct the quantity index. In the case of breeding livestock, the number of breeding livestock on January 1 is used as a measure of capital stock. Zero depreciation (as the value of the calf is assumed to be the same as that of the cull cow sent for slaughter at the end of the life period) is used to construct the rental value for the breeding livestock quantity index. In the case of farm real estate, three types of land (nonirrigated, irrigated, and pasture) and the value of buildings and structures are included. Acres of land and value of structures are aggregated by state-level cash rents and rental values, respectively, to obtain a farm real estate quantity index.

An implicit intermediate quantity index is calculated as the logarithmic difference between the rate of change in expenditures and the producer price index share weighted by the expenditures. To account for quantity changes in agricultural labor's contribution to agriculture production, data on hours worked for hired labor and unpaid and family labor, along with the wage rate for hired labor, are compiled. Wage compensation is used as a share in the aggregation of the farm labor quantity index.

Nitrogen Pollution

Excess nitrogen from agriculture calculated from nutrient mass balance accounting [i.e., the difference between nitrogen inputs (commercial fertilizer, animal manure, legume fixation) and nitrogen removed by harvested crops] is identified as potential nitrogen pollution. A positive nitrogen mass balance in the form of residual nitrogen remaining in the soil may be dissipated as nitrogen contamination in groundwater, surface water, or to the atmosphere. The National Research Council developed nitrogen and phosphate mass balances for cropland at the national level by aggregating nutrient inputs and withdrawals across all crops and nutrient sources.

Annual crop production reflects the removal of nitrogen from the soil through harvested crops. Historical data on secondary nitrogen (in the form of ammonia release, denitrification, soil erosion, surface runoff, and miscellaneous gaseous nitrogen losses) are not available. However, since the secondary nitrogen withdrawals will be re-deposited back into the soil, not accounting for secondary nitrogen withdrawals will not bias potential nitrogen pollution. The estimated nitrogen input, removal, and surplus for Nebraska for the period 1936–1997 are presented in table 1.

The negative numbers in the nitrogen surplus column of table 1 indicate that prior to World War II there was net removal of nitrogen from the soil. During the period 1961–1980, positive nitrogen balances indicate nitrogen was available in the soil for potential ground and/or surface water contamination. Evidence based on sampling of wells in Nebraska (Exner and Spalding; Muller et al.) suggests high levels of nitrogen contamination in irrigation wells.

The nitrogen fertilizer applied, residual nitrogen in the soil, corn production, acreage, and the corresponding nitrate contamination in the wells are used to validate the use of nitrogen surplus as a proxy for nitrate pollution. Unpublished data (Spalding) were obtained from 4,653 surveys of corn production representing 249,251 acres of the Central

Table 1. Estimated Nebraska Nitrogen Surplus or Potential Nitrogen Pollution, 1936–1997 (million pounds)

	N Inputs					
Year	Fertilizer	Manure	Legume	Total	N Removal	N Surplus
1936	0.0	117.1	259.2	376.3	275.2	101.2
1940	0.0	98.8	206.0	304.9	341.1	-36.2
1945	0.8	118.0	254.7	373.5	672.9	-299.4
1950	18.9	123.7	314.6	457.2	733.7	-276.5
1955	123.0	156.6	353.0	632.6	580.0	52.6
1960	276.5	151.9	315.7	744.1	920.0	-175.9
1965	507.8	177.0	326.3	1,011.1	862.2	148.9
1970	1,100.1	183.1	299.3	1,582.5	943.3	639.2
1975	1,084.6	198.3	305.9	1,588.8	1,171.3	417.5
1980	1,821.6	186.4	318.3	2,326.3	1,384.5	941.8
1985	1,777.8	179.6	322.3	2,279.8	1,787.7	492.1
1990	1,598.8	172.3	344.4	2,115.4	1,739.2	376.2
1991	1,657.2	178.9	346.1	2,182.2	1,758.0	424.1
1992	1,664.7	176.1	336.6	2,177.4	1,933.2	244.1
1993	1,761.6	178.2	338.5	2,278.4	1,589.1	689.2
1994	1,932.7	184.4	346.9	2,464.0	2,100.2	363.8
1995	1,745.1	182.0	347.4	2,274.5	1,694.4	580.1
1996	1,861.6	187.7	344.9	2,394.2	2,125.1	269.1
1997	1,846.9	190.7	374.5	2,412.1	2,049.8	362.3

Platte Natural Resource District in Nebraska. We used the unpublished data on the amount of nitrate contamination in wells from corn production acres from the same source for the period 1988–1995 to explain the effect of nitrogen surplus on nitrate contamination. The regression of nitrate contamination on excess nitrogen explained 42% of the variation (with an estimated coefficient of 0.034 and a t-value of 2.1), supporting the use of excess nitrogen as a proxy for nitrate contamination to the environment.

Empirical Application and Results

To examine the implications of treating environmental pollution as an undesirable output with weak disposability and as a normal input with strong disposability, the direct and indirect shadow prices are computed for nitrogen pollution abatement. The direct shadow prices [equations (6) and (7)] are retrieved as the ratio of the dual values (the gradient of the piecewise linear programming constraint of desirable output and nitrogen pollution). The indirect shadow prices [equations (10) and (11)] are recovered as the ratio of the derivative of the distance function with respect to output, aggregate input, and nitrogen pollution.

Averages of the gradient of the output, input, and nitrogen pollution constraints in the linear program recovered directly, and the derivatives of the parametric distance functions with respect to output, input, and nitrogen pollution are presented in table 2. Also presented in table 2 are the averages of output and input distance functions when nitrogen pollution is treated as an undesirable output and a normal input.

Table 2. Average Slope of the Output and Input Distance Functions

A. OUTPUT DISTANCE FUNCTION

Nitrogen Pollution	$\partial D_o/\partial Y_g$	$\partial D_o/\partial N$	Ratio [a]
Direct [b]	0.0049	0.0013	0.2597
Indirect [c]	0.0014	0.0001	0.0950

B. INPUT DISTANCE FUNCTION

Nitrogen Pollution	$\partial D_i/\partial N$	$\partial D_i/\partial X$	Ratio [a]
Direct [b]	0.0003	0.0040	0.0864
Indirect [c]	0.0002	0.0019	0.0974

Notes: D_o and D_i are the output and input distance functions, respectively; Y_g is a desirable output; X is the input; and N is potential nitrogen pollution.

[a] The ratios for the direct measures and indirect measures are defined in equations (6) and (7) and equations (10) and (11), respectively.

[b] The slopes in the direct approach are obtained from the dual values of the linear program.

[c] The slopes in the indirect approach are obtained from the ratios of the derivatives of the distance functions.

A comparison of the ratio of the output and input averages, respectively, using the indirect method (0.0950 and 0.0974) and the direct method (0.2597 and 0.0864) reveals differences. The following two conclusions can be drawn based on the ratio of the slopes. First, the difference between the average output and input distance ratio of the slopes is due to the disposability assumption—weak (strong) disposability in the output (input) distance function. Second, the difference in the ratio of the slopes between the direct and indirect methods within each disposability assumption is due to divergences in the approaches. In the direct method, we recover the shadow prices directly from the dual values of the linear programming constraint, while the indirect approach utilizes the derivatives of the distance function to estimate the shadow price in a two-stage process.

Within the direct approach, the difference in the output and input distance function slope ratios is due to the disposability assumption in the computation of the linear program. In the output distance function, apart from imposing a weak disposability assumption on nitrogen pollution, we are simultaneously maximizing desirable output and nitrogen pollution. In contrast, when imposing strong disposability on nitrogen pollution, nitrogen pollution is minimized along with other inputs. Due to the piecewise linear approximation, the slope or the gradient toward which the output (input) distance function maximizes (minimizes) leads to the differences in the average slope ratios (0.2597 and 0.0864) across output and input distance functions, respectively. In the indirect approach, the average output and input slope ratios (0.0950 and 0.0974), derived as the ratio of the first-order conditions, are nearly equal.

The average ratio of the input and output distance function slopes presented in table 2 is used to compute the shadow price of nitrogen pollution abatement. The differences in the average ratios of the slopes are reflected in the direct and indirect shadow price estimates of nitrogen pollution abatement treated as undesirable output (input) with weak (strong) disposability. In the direct approach, the ratios of the dual values for environmental pollution treated as undesirable output (input) and desirable output (input) are used in the computation of shadow prices in terms of the respective revenue or cost. Similarly, in the indirect approach, the ratio of the derivatives of the output (input) distance function with respect to output (input) and nitrogen pollution are used in the computation of the indirect shadow price in terms of revenue or cost, respectively.

Table 3 reports the estimated direct and indirect shadow prices and cost of nitrogen pollution abatement treated both as an undesirable output and as an input in real 1936 dollars. To convert a shadow price from units of index per unit of nitrogen pollution to dollars per unit of nitrogen pollution, we multiply the ratio of the slopes defined in equations (6) and (10) [equations (7) and (11)] by OQI (IQI) deflated revenue (cost) for the year in question. Since the revenue and cost are deflated by OQI and IQI, the units of the shadow price of nitrogen pollution abatement are in real 1936 dollars. Costs of nitrogen pollution abatement are computed by multiplying the real shadow price times the total nitrogen pollution generated by the Nebraska agriculture sector.

The direct and indirect shadow prices of potential nitrogen pollution abatement treated as an undesirable output (table 3, panel A) for the more recent periods 1971–80 ($2.87 and $1.18), 1981–90 ($3.48 and $1.43), and 1991–97 ($3.91 and $1.61) are comparatively higher than the average shadow prices for the entire period ($2.21 and $0.91). In contrast, the direct and indirect shadow prices of potential nitrogen pollution abatement treated as an undesirable output for the earlier periods 1936–50 ($1.06 and $0.44), 1951–60 ($1.53 and $0.63), and 1961–70 ($1.49 and $0.61) are lower than the average shadow price for the entire period. The average direct and indirect shadow prices of $2.21 and $0.91 over the time period 1936–1997 represent the opportunity cost in terms of revenue to reduce one pound of nitrogen pollution while maintaining agricultural production.

From panel B of table 3, a similar pattern was indicated by the direct and indirect shadow prices when nitrogen pollution was treated as an input. Shadow price estimates for the various time periods are shown as follows: 1936–50 ($0.53 and $0.60), 1951–60 ($0.88 and $0.99), 1961–70 ($1.05 and $1.18), 1971–80 ($2.05 and $2.31), 1981–90 ($3.31 and $3.73), and 1991–97 ($3.77 and $4.25). The average shadow prices of $1.73 and $1.95 over the 1936–1997 time period represent the increased cost due to strong disposability of nitrogen pollution. A negative (i.e., more nitrogen was extracted from the soil than was applied) and positive (i.e., more nitrogen was retained in the soil leading to potential nitrogen contamination) excess nitrogen surplus prior to 1960 and after 1960, respectively, is reflected in the negative and positive shadow values.

The shadow price estimated from the output distance function includes the cost of abating pollution and the reduced output resulting from treating nitrogen pollution as an undesirable output. In comparison, the shadow price estimated from the input distance function reflects the cost of abating pollution. As a result of the differences between the output distance function and input distance function, the shadow price reflected in terms of revenue is higher than the shadow price for the input distance function for the direct approach. For the indirect approach, without the direct influence of the disposability assumption, the input distance shadow prices are higher than the output distance function shadow prices. The shadow prices from the output distance function should be equal to the shadow prices from the input distance function provided revenue is equal to cost. This is seldom the case for an aggregate sector like Nebraska agriculture.

Care must be exercised in comparing shadow prices reported in table 3 to nitrogen fertilizer costs. The estimated shadow prices are expressed as real 1936 dollars per pound of nitrogen pollution. One pound of nitrogen pollution requires multiple pounds of nitrogen fertilizer to yield that pound of pollution.

Table 3. Average Shadow Prices and Cost Estimates of Nitrogen Pollution Abatement, Nebraska Agriculture Sector (1936–1997)

A. OUTPUT DISTANCE FUNCTION

	Direct Approach		Indirect Approach	
Time Period	Shadow Price[a] ($/pound)	Cost[b] ($ million)	Shadow Price[a] ($/pound)	Cost[b] ($ million)
1936–50	1.06	-208.4	0.44	-85.8
1951–60	1.53	-218.0	0.63	-89.7
1961–70	1.49	400.8	0.61	165.0
1971–80	2.87	1,871.7	1.18	770.4
1981–90	3.48	1,616.7	1.43	665.4
1991–97	3.91	1,660.0	1.61	683.3
1936–1997	2.21	729.1	0.91	300.1

B. INPUT DISTANCE FUNCTION

	Direct Approach		Indirect Approach	
Time Period	Shadow Price[a] ($/pound)	Cost[b] ($ million)	Shadow Price[a] ($/pound)	Cost[b] ($ million)
1936–50	0.53	-102.0	0.60	-115.0
1951–60	0.88	-126.7	0.99	-142.7
1961–70	1.05	287.2	1.18	323.5
1971–80	2.05	1,354.1	2.31	1,525.6
1981–90	3.31	1,527.7	3.73	1,721.1
1991–97	3.77	1,581.2	4.25	1,781.4
1936–1997	1.73	644.5	1.95	726.2

[a] The annual shadow prices are averaged across the time periods and measured in real 1936 dollars per pound of nitrogen pollution.

[b] Cost of nitrogen pollution abatement is computed as the product of the real shadow price and total nitrogen surplus. The annual cost of nitrogen pollution abatement is the mean over the time periods.

The cost of abating nitrogen pollution treated as undesirable output is 2.8% (direct approach) and 3.8% (indirect approach) of farm revenue over the entire 1936–1997 time period. Similarly, the cost of abating environmental pollution treated as a normal input is 6.5% (direct approach) and 7.3% (indirect approach) of the farm cost of production over this same time period.

As demonstrated by this study, the shadow price of environmental pollution abatement treated as an undesirable output with weak disposability or as a normal input with strong disposability can be estimated. It is much more appropriate to assume environmental pollution as a joint output with desirable output because it can identify environmental pollution in the economic (positive marginal rate of transformation) as well as in the non-economic (negative marginal rate of transformation) zone compared to the normal input approach with strong disposability. Between estimation procedures, the direct approach is less prone to bias and error because it is directly recovered from the linear programming constraint compared to the indirect two-stage approach involving nonparametric linear programming in the first stage followed by parametric regression analysis in the second stage.

Conclusions and Implications

The effects of treating environmental pollution as an undesirable output (weak disposability) as well as a normal input (strong disposability) on the direct and indirect shadow price estimates of nitrogen pollution abatement are addressed in this study. The shadow price estimates using Nebraska data for 1936–1997 are the abatement costs of reducing nitrogen pollution by one pound. When multiplied by the estimated nitrogen pollution levels, the overall cost of abating nitrogen pollution was derived. For the 1936–1997 period, the annual average estimated real abatement costs range from $300 to $729 million. Overall, the results demonstrate that the differences in the shadow price estimates are due to the differences in the disposability assumption and estimation procedure.

The shadow price of nitrogen pollution abatement treated as an undesirable output represents the loss from reducing nitrogen pollution while maintaining agricultural production. In contrast, the shadow price of nitrogen pollution abatement treated as an input reflects the increased cost. Higher shadow prices were recovered for the direct approach than for the indirect approach in the output distance function. The converse was true in the input distance function. Differences between the two approaches are due to the disposability assumption. The weak disposability assumption associated with the output distance function imposes a cost of disposing of nitrogen pollution. In contrast, the strong disposability assumption associated with the input distance function does not impose a cost. This difference in the disposability assumptions leads to relatively higher shadow price/cost for the direct approach and output distance function.

Shadow price differences between the output distance function and the input distance methods are influenced by the difference between agriculture revenue and agriculture cost. The results of this study can be useful for further research, particularly analyses related to (*a*) the use of shadow prices to adjust the traditional Tornqvist-Theil productivity measures for environmental pollution; (*b*) the disposability assumption, estimation approach, and whether to treat environmental pollution as an output or an input; and (*c*) estimation of the demand for environmental pollution in a system of equations.

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