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Adjustments of Agricultural Productivity for Nitrogen Effluent in the Great Plains

Jon Rezek and Richard Perrin[1]

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Abstract:

Traditional measures of agricultural productivity only incorporate those inputs and outputs that are recorded in market transactions. However, such measures do not account for externalities such as environmental damage. This study uses an output distance function framework to estimate a Malmqvist productivity index for a panel of Great Plains states then adjusts this index by incorporating nitrogen effluent into the analysis. We estimate that long-run environmentally-adjusted productivity growth was approximately 13 percent below the unadjusted rate during the sample period. However the environmentally sensitive productivity rate actually exceeded the unadjusted rate in recent years, reflecting reductions in the discharge of agricultural nitrogen into the environment.

[1] Visiting Assistant Professor, jpr3@cobilan.msstate.edu, Department of Economics, Mississippi State University, and Professor, rperrin@unl.edu, Department of Agricultural Economics, University of Nebraska, Lincoln. Financial support from a USDA/NRI grant and from the Agricultural Research Service, UNL, is acknowledged.

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The productivity of agriculture in the U.S. has been studied vigorously. Measured performance rates in the vicinity of two percent annually in the last half of the twentieth century have been an important factor in feeding the exponentially-expanding world population at lower, rather than higher, food prices. Yet there is considerable concern about the cost of this productivity in terms of damage to the environment, and this concern translates into mistrust of the standard measures of productivity. Clearly it is useful to adjust productivity measures for environmental impacts, but the difficulties of accomplishing this adjustment are so great that there have been few such attempts, and any attempt can at best be only a relatively rudimentary and partial adjustment. In this study we adjust agricultural productivity measures for nitrogen effluents in four Great Plains states.

Adjusting productivity measurements for environmental impacts

Some perspective on the general issue considered here is offered by the principle of conservation of mass and energy. This principle implies that if everything were measured completely, productivity indexes (indexes of "output" divided by indexes of "input") should always equal unity, and productivity gains should always be zero. But productivity is an anthropocentric notion, not a strictly technological one, so in measuring productivity gains we only count those inputs and outputs that we care about. Furthermore, traditional productivity measures only count those inputs and outputs for which there are observed market transactions, a subset of all those that affect our welfare. The inputs and outputs that are missing, including externalities such as environmental impacts, are those with no recorded transactions. The difficulty of incorporating these goods and/or bads into productivity measures is that we generally have no estimates of their quantities nor of shadow prices that would allow us to weight them along with traditional inputs and outputs for which market prices provide convenient weights.

An environmentally-adjusted productivity index would thus be one that includes changes in the quantity (flow) of environmental goods or bads, with associated welfare weights comparable to the prices that are used for weighting marketed inputs and outputs. Most of the theory of productivity measurement has ignored consumer welfare considerations, and instead has focused on measurements of the change in the feasible technology set defined in terms of traditional inputs and outputs. Changes in this technology set can be measured using various empirical techniques, and along with these estimates of the technology set come estimates of the tangent hyper-planes that reflect producer shadow prices. These shadow prices are explicitly or implicitly used in the measurement of productivity change derived from estimates of the technology set. This is a perfectly appropriate way to estimate productivity if there are no market failures, for then at observed equilibrium data points, the implicit shadow prices (measured by the hyper-planes tangent to the production technology set) are proportional to the appropriate consumer welfare weights (measured by the price hyper-planes tangent to consumers' utility functions.) Extensions of productivity theory to incorporate environmental goods or bads have generally continued on this avenue of measuring changes in the technology set, implicitly using shadow prices to weight goods and bads, because consumer-relevant prices for the environmental amenities are simply not available. The study reported here continues in this tradition of estimating adjusted productivity by examining the technology set with its implicit shadow prices.

The earliest effort to adjust productivity performance estimates for undesirable outputs was reported by Pittman (1983), who calculated shadow prices from abatement costs to make environmental adjustments to a multilateral productivity index for a sample of pulp and paper mills. Fare, Grosskopf, Lovell and Pasurka (1989) were the first to adjust productivity performance for environmental bads by explicitly including effluents in an estimated technology set for Pittman's data. They used data envelopment analysis (DEA) to estimate a non-parametric piece-wise linear production set, reporting the environmentally-adjusted efficiency of the mills. Fare, Grosskopf, Lovell and Yaisawarng (1993)also utilized an output distance function to represent the technology of the paper (and effluent) producing mills. They estimated a translog form of the distance function using the Aigner-Chu non-stochastic linear programming estimation approach. Hailu and Veeman (2000) recently utilized this same approach to estimate an input distance function to measure pollution-adjusted productivity for the aggregate Canadian pulp and paper industry.

In what follows, we first describe the output distance function and the associated Malmqvist productivity index, then describe the data and empirical estimation procedures, after which we report and interpret both unadjusted and adjusted productivity measures.

Output distance function

Consider a technology which utilizes a set of $\boldsymbol{x} \in \Re^N_+$ inputs to produce a set of $\boldsymbol{y} \in \Re^M_+$ outputs, of which $\boldsymbol{y_d} \in \Re^D_+$ are desirable and $\boldsymbol{y_u} \in \Re^U_+$ are undesirable. Let the output set, P($\boldsymbol{x}$), be a closed, bounded, convex set which describes all technically feasible output vectors. In this analysis we describe technology using Shephard's (1970) output distance function, $D_O(\boldsymbol{x}, \boldsymbol{y})$, which completely expresses the technical relationship between inputs and outputs as a mapping of a multiple-output, multiple-input production process onto a real line. It measures the minimum scalar, q, such that $\boldsymbol{y}/q$ remains in the feasible set:

$$D_O(\boldsymbol{x}, \boldsymbol{y}): \min\{q : \boldsymbol{y}/q \in P(\boldsymbol{x})\}. \qquad (1)$$

For each observation the output distance function measures the greatest radial output expansion feasible given the observed level of inputs. The distance function value for a given observation equals 1 if and only if the observation is a member of the frontier of the output set P($\boldsymbol{x}$). Values between 0 and 1 indicate production on the interior of the output set P($\boldsymbol{x}$). This distance function value is equivalent to the inverse of the Farrell (1957) measure of technical efficiency. Hence, for cross-sectional input/output observations a distance function value of 1 indicates an efficient or frontier point while values less than 1 indicate inefficiency in production.

The output distance function is a continuous function of $\boldsymbol{x}$ and $\boldsymbol{y}$, and exhibits homogeneity of degree 1 in $\boldsymbol{y}$. It is assumed to be non-decreasing in $\boldsymbol{y_d}$ and non-increasing in $\boldsymbol{y}_u$ – increases in desirable outputs lead to increases in efficiency, while increases in undesirables lead to reductions in efficiency measures. Further, the distance function is quasi-concave and non-increasing in $\boldsymbol{x}$. Finally, $D_O(\boldsymbol{x}, \boldsymbol{y})$ is dual to the revenue function under the regularity conditions shown in Shephard (1970).

Three additional properties of the output distance function make it ideal for the measurement of environmentally-adjusted productivity. First, the output distance function can be completely described in quantity space, which is preferable when price information is incomplete or nonexistent as is the case when effluents are included in the analysis. Second, the output distance function allows for weak disposability of outputs. Weak output disposability assumes that a radial contraction of outputs is feasible with a given set of inputs. That is, if $\boldsymbol{y} \in P(\boldsymbol{x})$ and $\boldsymbol{q} \in [0,1]$ then $\boldsymbol{qy} \in P(\boldsymbol{x})$. The more rigorous alternative assumption, free output disposability, states that if $\boldsymbol{y}' \leq \boldsymbol{y} \in P(\boldsymbol{x})$ then $\boldsymbol{y}' \in P(\boldsymbol{x})$. Free disposability implies that if the output bundle $\boldsymbol{y}$ is feasible then one or more of the outputs could be disposed of costlessly with the new output bundle remaining in the feasible set. Because effluents may not necessarily be eliminated without a reduction in some desirable output (or an increase in abatement inputs) the weak disposability assumption is more intuitively appealing. The output distance function is compatible with this assumption.

Finally, Shephard (1970) shows that the derivatives of the output distance function with respect to each of the outputs generate their relative shadow prices,

$$\partial D_{Oi} (\boldsymbol{x}, \boldsymbol{y}) / \partial y_i = p_i (\boldsymbol{x}, \boldsymbol{y}) \qquad (2)$$

where p_i is the shadow price of output i. Using an estimation technique originated by Aigner and Chu (1968), the signs of these derivatives can be restricted to allow asymmetric treatment of desirable and undesirable outputs. Shadow prices of desirable outputs are restricted to be non-negative – imposing the assumption that $D_O(\boldsymbol{x}, \boldsymbol{y})$ is non-decreasing in $\boldsymbol{y}_d$. Shadow prices of undesirable outputs are restricted to be non-positive – imposing the alternative assumption that $D_O(\boldsymbol{x}, \boldsymbol{y})$ is non-increasing in $\boldsymbol{y}_u$. These restrictions credit producers for increasing desirable output as well as reducing undesirables.

Malmqvist productivity index

The distance function approach can be extended to calculate changes in productivity over time by applying panel (or time-series) data. Caves et. al. (1982) propose the output-based Malmqvist index to calculate total factor productivity (TFP) growth using four distance function measures. Fare et. al. (1994) further show that the output-based Malmqvist TFP index can be written as:

$$M_O(y^{t_1}, x^{t_1}, y^{t_2}, x^{t_2}) = \frac{D_O^{t_2}(x^{t_2}, y^{t_2})}{D_O^{t_1}(x^{t_1}, y^{t_1})}\left[\left(\frac{D_O^{t_1}(x^{t_2}, y^{t_2})}{D_O^{t_2}(x^{t_2}, y^{t_2})} \times \frac{D_O^{t_1}(x^{t_1}, y^{t_1})}{D_O^{t_2}(x^{t_1}, y^{t_1})}\right)^{\frac{1}{2}}\right] \quad (3)$$

where t_1, t_2 are two periods under comparison.

Fare *et al.* decompose equation (3) into two constituent parts, change in technical efficiency and technical change. Each term to the left of the brackets represents the Farrell efficiency of a given observation in period t as compared with other period t observations. If the observation is efficient relative to its contemporaneous counterparts then no radial expansion of outputs is feasible and $D_o(\boldsymbol{x}, \boldsymbol{y}) = 1$. The ratio of these distance function values represents the change in technical efficiency over time and measures the degree to which the observation has migrated towards (or away from) the time-specific reference frontier from period t_1 to period t_2.

The Fare *et al*. decomposition further identifies the bracketed term as technical change. Inside the bracket, $D^{t_1}(\boldsymbol{x}^{t_2}, \boldsymbol{y}^{t_2})$ represents the efficiency of a period t_2 observation when compared with a panel of period t_1 observations. Technical advancement may make the period t_2 observation appear infeasible relative to the technology available in period t_1, therefore $D^{t_1}(\mathbf{x}^{t_2}, \mathbf{y}^{t_2})$ may be greater than 1. The term $D^{t_2}(\boldsymbol{x}^{t_1}, \boldsymbol{y}^{t_1})$ represents the efficiency of a period t_1 observation when compared with a panel of t_2 observations. Technical improvement over time renders the period t_1 observation inefficient relative to the period t_2 frontier, therefore $D^{t_2}(\boldsymbol{x}^{t_1}, \boldsymbol{y}^{t_1})$ is expected to be significantly below 1. The geometric mean of the two terms within the parenthesis indicates how rapidly the frontier has advanced over time.

Data and empirical estimation procedures

In our empirical application, we consider four Great Plains states (Kansas, Nebraska, Oklahoma and South Dakota) from 1960-1996. We use state-level index data compiled by the USDA (1998a) on two outputs (crops and livestock) and four inputs (land, labor, capital and materials) to estimate the baseline Malmqvist index. This data was chosen to obtain a straightforward comparison with the Tornqvist-Theil TFP indexes computed by the USDA (1998b) using the conventional index number approach.[2]

In this study we adjust agricultural productivity to account for the release of nitrogen into the rural environment. Nitrogen is one of the major contaminants in the Great Plains region with the potential to cause damage to fish and other wildlife, health-related damage, the loss of recreational opportunities and a reduction in ground and

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[2] The index number approach calculates the productivity index as an output index divided by an input index. See USDA (1998a) for a detailed explanation of this approach.

surface water quality. We use *excess nitrogen*, computed using the NRC's (1993) nutrient mass balance accounting methodology, as a measure of total effluent. Excess nitrogen is computed as the difference between nitrogen inputs, from commercial fertilizers, animal waste and the nitrogen fixing legumes, and the nitrogen extracted from the soil in the form of harvested crops. The resulting number indicates the total nitrogen added to the state's soil during a given year. It serves here as a measure of the nitrogen effluent produced by the agricultural sector.

To empirically estimate each of the output distance functions in equation (3) we follow the non-stochastic linear programming approach developed by Fare et. al. (1993). The LP method is often used in lieu of stochastic estimation when detrimental by-products are produced because it allows the appropriate inequality constraints on the output shadow prices to be readily imposed. This approach has similarly been applied in the context of electricity production (Coggins and Swinton, 1996 and Swinton, 1998) and pulp and paper production (Hailu and Veeman, 2000).

We estimate a translog specification of the output distance function as given by:

$$\ln D(\mathbf{x}, \mathbf{y}) = \alpha_0 + \sum_{i=1} \alpha_i (\ln y_i) + \sum_{j=1} \beta_j (\ln x_j) + (0.5) \sum_{i=1} \sum_{i=1} \alpha_{ii} (\ln y_i)(\ln y_i)$$

$$+ (0.5) \sum_{j=1} \sum_{j=1} \beta_{jj} (\ln x_j)(\ln x_j) + (0.5) \sum_{i=1} \sum_{j=1} \gamma_{ij} (\ln y_i)(\ln x_j)$$

$$+ \mu_1 (t) + (0.5) \mu_2 (t^2) + \sum_{j=1} ?_i (\ln y_i)(t) \qquad (4).$$

The Fare *et al.* (1993) technique seeks the best-fit distance function subject to the theoretical constraints implied by the properties of the output distance function. We solve the following linear program using the GAMS package:

$$\max_{\alpha,\beta,\delta,\gamma,\mu} \quad \sum_{t=1}^{T}\sum_{k=1}^{K} \ln D_k^t(x^t, y^t) \tag{5}$$

subject to:

$$\ln D(\boldsymbol{x}, \boldsymbol{y}) \leq 0 \tag{6}$$

$$\partial \ln D(\boldsymbol{x}, \boldsymbol{y}) / \partial \ln \boldsymbol{y_d} \geq 0 \tag{7}$$

$$\partial \ln D(\boldsymbol{x}, \boldsymbol{y}) / \partial \ln \boldsymbol{y_u} \leq 0 \tag{8}$$

$$\Sigma_i \alpha_i = 1 , \ \Sigma_i \alpha_{ii} = 0 , \Sigma_i \gamma_{ij} = 0 \tag{9}$$

$$\alpha_{ij} = \alpha_{ji} \ , \ \beta_{ij} = \beta_{ji} \tag{10}$$

where the panel is *T* periods in length and consists of *K* cross-sections. Equation (6) requires that each observation remain in the feasible set. Equation (7) imposes non-negative shadow prices on the desirable outputs while equation (8) imposes non-positive shadow prices on the undesirable outputs. Equation (9) imposes homogeneity of degree 1 on outputs. Equation (10) requires the interaction parameters of the translog functional form to be symmetric. These restrictions are theoretically consistent with the properties of the output distance function and allow for the estimation of efficiency measures and the calculation of the accompanying Malmqvist productivity index.

Initially we run the linear program suggested by equations (5-10) excluding effluents. The year 1960 serves as t=1, the reference technology. The results are used to calculate the traditional or unadjusted Malmqvist TFP index. We run the LP again, this time incorporating the undesirable into the analysis thereby adjusting the original baseline measure to account for both desirable and undesirable output production. The parameter results of both LP's are displayed in Appendix 1.

Unadjusted productivity measures

The four Farrell efficiency measures from equation (3) are calculated for each observation to complete the output-based Malmqvist productivity index. Table 1 summarizes the results, reporting the averages across the four-state panel. Column 2 displays the Malmqvist TFP index, representing both technical change and change in efficiency over time. It shows, for instance, that average agricultural productivity in the region increased by 2.6 percent from 1960 to 1961. The conventional index number approach, shown in column 5, indicates that productivity *declined* by 2.6 percent during that time.

On balance the Malmqvist approach tends to yield lower productivity increases than the Tornqvist-Theil index. The Malmqvist measure shows only a 41 percent increase in productivity during the sample period (equivalent to a compound rate of 0.97% annually), as compared to a 77 percent increase (1.60% annually) using the index number approach. However, the Malmqvist index is slightly more stable than the index number estimates. The results are not unexpected since the Malmqvist index only measures the extent of the production frontier's movement over time in a radial fashion, while the Tornqvist-Theil index incorporates both the expansion of the frontier and the change in relative input and output prices. The Malmqvist index does not require the assumption of technical and allocative efficiency as is implied by the Tornqvist-Theil index.

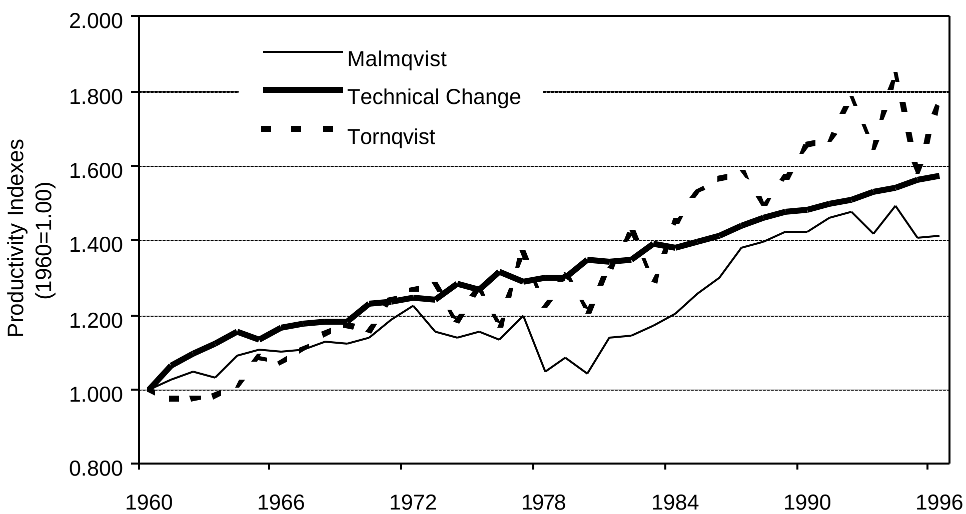
Table 1: Unadjusted Average of Estimates of Total Factor Productivity Indices

Year	Malmqvist TFP Index	Technical D	D Technical Efficiency	Tornqvist Theil TFP Index
1960	1.000	1.000	1.000	1.000
1961	1.026	1.066	0.963	0.974
1962	1.045	1.093	0.957	0.977
1963	1.029	1.121	0.918	0.979
1964	1.092	1.155	0.945	1.011
1965	1.107	1.132	0.978	1.086
1966	1.103	1.164	0.948	1.070
1967	1.107	1.176	0.941	1.104
1968	1.130	1.183	0.955	1.148
1969	1.123	1.183	0.949	1.174
1970	1.138	1.231	0.924	1.159
1971	1.185	1.234	0.962	1.236
1972	1.223	1.246	0.982	1.267
1973	1.155	1.238	0.933	1.279
1974	1.140	1.285	0.887	1.186
1975	1.155	1.267	0.911	1.268
1976	1.131	1.314	0.861	1.174
1977	1.198	1.288	0.930	1.368
1978	1.049	1.300	0.808	1.225
1979	1.085	1.300	0.834	1.305
1980	1.045	1.345	0.776	1.211
1981	1.139	1.343	0.848	1.331
1982	1.144	1.346	0.850	1.421
1983	1.170	1.389	0.842	1.292
1984	1.205	1.383	0.872	1.451
1985	1.258	1.394	0.902	1.529
1986	1.298	1.413	0.918	1.565
1987	1.379	1.437	0.959	1.580
1988	1.396	1.463	0.953	1.499
1989	1.421	1.476	0.962	1.568
1990	1.421	1.480	0.959	1.655
1991	1.458	1.499	0.972	1.671
1992	1.476	1.510	0.976	1.780
1993	1.418	1.530	0.926	1.651
1994	1.495	1.542	0.971	1.846
1995	1.409	1.560	0.904	1.586
1996	1.414	1.575	0.900	1.772

Column 3 shows the estimate of the technical change component over the period, a 58 percent increase (1.27% annually.) This corresponds to the bracketed term in equation (3). These results show that technical change has occurred at a much smoother rate than is indicated by the Tornqvist-Theil index. By separating technical change from efficiency change the long-run trend can be isolated from the more transitory effects of mere changes in efficiency from one time period to the next. The Malmqvist technical change measure and the Tornqvist-Theil TFP index follow a similar trend, however, the technical change measure is less erratic and therefore may be a better predictor of longterm productivity growth prospects. Figure 1 provides a graphical representation of the Malmqvist and Tornqvist-Theil indexes as well as the technical change portion of the Malmqvist index.

Figure 1: Malmqvist Productivity Index,

Technical Change Component and Tornqvist Productivity Index



Finally, column 4 shows the average efficiency change in the panel over time. This measure coincides with the term outside the brackets in equation (3). There was a general increase in inefficiency starting in 1974 and persisting until approximately 1984. The trend is consistent across all states in the panel. Hialu and Veeman (2000), using a similar technique, also observe this pattern in their time-series analysis of the Canadian pulp and paper industry. They cite the energy crisis and the prolonged inflation present at that time as potential sources of increased inefficiency. These forces may have undermined U.S. agricultural efficiency as well. Due to this study's use of panel data we provide even more robust evidence of the inefficiency present in the late 1970's and early 1980's than the Hialu and Veeman work, reinforcing their observations.

Environmentally-adjusted productivity

The results of the second LP, including excess nitrogen as a detrimental output, are used to calculate the adjusted Malmqvist index. Average results are summarized in Table 2. Individual state results are shown in Appendix 2. The technical change component of the Malmqvist TFP index is reported; it is indicative of the long-run trend in productivity change because it excludes the short-run effects of year-to-year variation in efficiency. Column 2 shows the unadjusted Malmqvist technical change index, repeated from Table 1 for convenient reference. Column 3 shows the Malmqvist technical change results when excess nitrogen is included in the analysis. During the sample period, the unadjusted index shows growth of 58 percent between 1960 and 1996. However, after accounting for increases in nitrogen effluent, growth in the region is adjusted downward to 48 percent during the sample period.

Columns 4 and 5 compare the growth rate of adjusted and unadjusted technical change, respectively. The magnitude and sign of the annual growth rates are similar across the two measures. There is broad agreement between the two measures, adjustments are minimal and generally consistent from year to year. However, from 1960-1996 productivity growth is adjusted downward by about 13 percent when excess nitrogen production is incorporated - from 1.26 percent annually to 1.10 percent annually. In the period 1960-1979 unadjusted growth far outpaces adjusted growth, but by the 1980's they are about equal, and after 1989 the adjusted rate actually exceeds the unadjusted rate. Here we see that the environmental adjustment works both ways – it reduces estimated productivity when the rate of pollution is increasing, and increases the estimate when the pollution rate is falling.

Table 2: Adjusted and Unadjusted Malmqvist

Technical Change Indices and Growth Rates

Year	Unadjusted Malmqvist Technical D Index	Adjusted Malmqvist Technical D Index	Growth Rate of Unadjusted Technical D	Growth Rate of Adjusted Technical D
1960	1.000	1.000	?	?
1961	1.066	1.080	6.39%	7.68%
1962	1.093	1.099	2.50%	1.73%
1963	1.121	1.121	2.58%	1.99%
1964	1.155	1.156	2.95%	3.10%
1965	1.132	1.117	-2.02%	-3.45%
1966	1.164	1.143	2.77%	2.28%
1967	1.176	1.151	1.08%	0.72%
1968	1.183	1.151	0.57%	0.02%
1969	1.183	1.144	-0.02%	-0.66%
1970	1.231	1.198	4.01%	4.63%
1971	1.234	1.194	0.20%	-0.35%
1972	1.246	1.201	0.95%	0.64%
1973	1.238	1.185	-0.59%	-1.39%
1974	1.285	1.231	3.74%	3.87%
1975	1.267	1.207	-1.44%	-2.00%
1976	1.314	1.254	3.60%	3.78%
1977	1.288	1.219	-2.00%	-2.76%
1978	1.300	1.228	0.93%	0.70%
1979	1.300	1.223	0.07%	-0.40%
1980	1.345	1.269	3.41%	3.70%
1981	1.343	1.264	-0.19%	-0.39%
1982	1.346	1.267	0.26%	0.21%
1983	1.389	1.311	3.11%	3.41%
1984	1.383	1.297	-0.45%	-1.04%
1985	1.394	1.306	0.83%	0.69%
1986	1.413	1.325	1.36%	1.44%
1987	1.437	1.350	1.64%	1.82%
1988	1.463	1.375	1.84%	1.87%
1989	1.476	1.386	0.85%	0.82%
1990	1.480	1.390	0.31%	0.24%
1991	1.499	1.408	1.22%	1.29%
1992	1.510	1.419	0.79%	0.76%
1993	1.530	1.439	1.27%	1.40%
1994	1.542	1.450	0.80%	0.80%
1995	1.560	1.470	1.19%	1.33%
1996	1.575	1.484	0.92%	0.99%
Average 1960-69			1.87%	1.49%
Average 1970-79			0.95%	0.67%
Average 1980-89			1.27%	1.25%
Average 1990-96			0.93%	0.97%
Average 1960-96			1.26%	1.10%

In effect, states are being credited for shifting their output mix away from excess nitrogen and towards crops and livestock. This result is encouraging from the perspective of environmental sustainability, and it reflects the benefits of the hidden research costs and technology adoption costs that have led to the reduced pollution.

Figure 2: Malmqvist Technical Change Indices

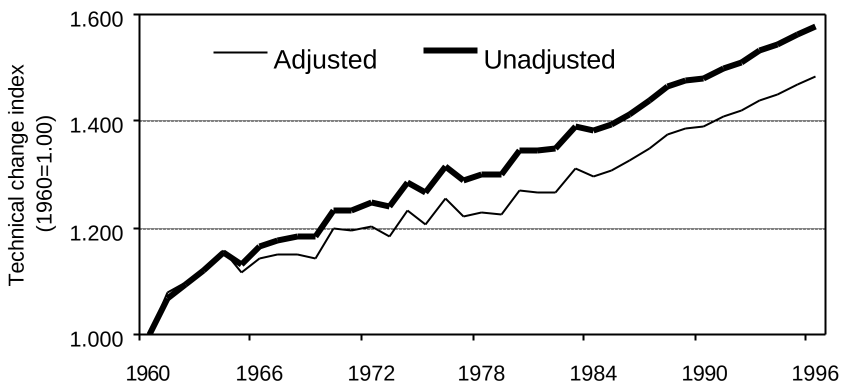


Figure 2 shows the technical change indexes graphically. The gap between the adjusted and unadjusted technical change measures grows until approximately 1985, after which the difference is merely maintained, reflecting more similarity in growth rates across measures. Post-1985, growth rates are actually more likely to be adjusted upward than downward after including the undesirable into the model.

Conclusions

In this study we have examined agricultural productivity in a panel of four Great Plains states. We estimated the technology set using a translog specification of an output distance function using the Aigner-Chu linear programming approach. One such estimate of the technology included only traditional outputs and inputs, and a second estimate added a measure of the quantity of nitrogen discharged into the environment by agricultural production activities.

Ignoring nitrogen pollution, the standard Tornqvist-Theil index measured productivity gain at an average rate of 1.57 percent for the 1960-96 period, whereas the Malmqvist productivity index measure was 0.96 percent. The Malmqvist technical change index, an estimate of the rate at which the production set itself expanded, yielded 1.27percent. This latter figure is perhaps a better measure of productivity, since in theory it measures the underlying rate of technological change, whereas the productivity measures include transient factors such as weather or other inefficiencies.

When we include nitrogen pollution, the average estimate of Malmquist productivity falls by about 17 percent to 0.8 percent per year, whereas the estimate of Malmquist technical change falls by about 13 percent to 0.86 percent per year. Beyond these average figures, it is notable that the standard productivity rates far exceeded the adjusted rates prior to the mid-1980's after which the pollution-adjusted rate began to exceed the standard rate. This turnaround reflects the societal benefits of public expenditures on research to produce more environmentally-friendly agricultural technology, and of private expenditures to adopt these and other technologies that increase the output of crops and livestock relative to nitrogen effluent.

By incorporating nitrogen effluent into our production model we have in some sense provided a more complete rendering of the agricultural production process for the purposes of productivity measurement. The productivity adjustment remains somewhat rudimentary because the welfare weights on the bad are the opportunity costs implied by the technology rather than those representing consumer preferences. However, in the absence of information on such values, the method employed here provides a reasonable and theoretically consistent way of accounting for the production of environmental bads.

References

Aigner, D.J. and S.F. Chu. "On Estimating the Industry Production Function." *American Economic Review 13* (1968):826-839.

Caves, D.W., L.R. Christiansen and W.E. Diewert. "The Economic Theory of Index Numbers and the Measurement of Input, Output and Productivity." *Econometrica 50* (1982):1939-1414.

Coggins, J.S., and J.R. Swinton. "The Price of Pollution: A Dual Approach to Valuing SO_2 Allowances." *Journal of Environmental Economics and Management 30* (1996):58-72.

Fare, Grosskopf, Lovell and Pasurka. "Multilateral Productivity Comparisons When Some Outputs Are Undesirable: A Nonparametric Approach." *Review of Economics and Statistics 71* (1989):90-98.

Fare, R., S. Grosskopf, C.A.K. Lovell, and S. Yaisawarng. "Derivation of Shadow Prices for Undesirable Outputs: A Distance Function Approach." *Review of Economics and Statistics 75* (1993):374-380.

Fare, R. S. Grosskopf, M. Norris, and Z. Zhang. "Productivity Growth, Technical Progress and Efficiency Change in Industrialized Counties." American Economic Review 84 (1994):66-84.

Farrell, M.J. "The Measurement of Productive Efficiency." *Journal of the Royal Statistical Society Ser. A 120* (1970):253-281.

Hailu, A. and T.S. Veeman. "Environmentally Sensitive Productivity Analysis of the Canadian Pulp and Paper Industry, 1959-1994: An Input Distance Function Approach." Journal of Environmental Economics and Management 40 (2000):251-274.

National Research Council. *Soil and Water Quality: An Agenda for Agriculture*. Washington D.C.: National Academy Press, 1993.

Pittman, R.W. "Multilateral Comparisons with Undesirable Outputs." *Economic J. 93* (1983):883-891.

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

Swinton, J.R. "At What Cost do We Reduce Pollution? Shadow Prices of SO_2 Emissions." *Energy Journal 19* (1998):63-83.

USDA Economic Research Service. "Agricultural Productivity in the United States." Agricultural Information Bulletin No. 740 (1998a).

USDA Economic Research Service "Patterns of State Productivity Growth in the U.S. Farm Sector." Staff Paper No. 9804 (1998b).

APPENDIX 1:

Parameter estimates of the output distance functions

Parameter	2 output / 4 input	3 output / 4 input
a_0	0.241	0.196
a_1	0.415	0.323
a_2	0.585	0.677
a_3		0.000
b_1	-0.274	-0.212
b_2	-1.055	-0.968
b_3	-0.043	-0.009
b_4	-0.649	-0.664
b_{11}	0.445	0.872
b_{12}	0.223	-0.001
b_{13}	0.088	0.016
b_{14}	-0.319	-0.374
b_{22}	0.025	-0.265
b_{23}	-0.124	-0.113
b_{24}	-0.849	-0.632
b_{33}	0.092	-0.007
b_{34}	-0.031	0.043
b_{44}	0.236	0.240
a_{11}	0.067	0.057
a_{12}	-0.067	-0.057
a_{13}		0.001
a_{22}	0.067	0.058
a_{23}		-0.001
a_{33}		.000
g_{11}	-0.174	0.059
g_{12}	0.174	-0.058
g_{13}		-0.002
g_{21}	0.046	0.159
g_{22}	-0.046	-0.156
g_{23}		-0.003
g_{31}	0.029	0.040
g_{32}	-0.029	-0.039
g_{33}		-0.001
g_{41}	-0.101	-0.289
g_{42}	0.101	0.288
g_{43}		0.001
m_1	-0.013	-0.009
m_2	0.000	0.000
$?_1$	0.011	0.014
$?_2$	-0.011	-0.014
$?_3$		0.000

Subscripts on outputs correspond to (1) livestock, (2) crops and (3) excess nitrogen, respectively
Subscripts on inputs correspond to (1) capital, (2) land, (3) labor and (4) materials, respectively.

APPENDIX 2:

Kansas Productivity Indexes

Year	TT	TFP	D TE	Tech D	TFP*	D TE*	Tech D*?
1960	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1961	0.989	1.035	0.964	1.073	1.061	0.974	1.089
1962	0.969	1.073	0.963	1.114	1.107	0.974	1.136
1963	0.942	1.041	0.896	1.161	1.083	0.909	1.192
1964	0.982	1.120	0.960	1.167	1.169	0.982	1.190
1965	1.036	1.108	0.976	1.135	1.143	1.006	1.136
1966	0.988	1.074	0.904	1.187	1.030	0.882	1.168
1967	1.052	1.073	0.907	1.182	1.029	0.892	1.154
1968	1.120	1.106	0.939	1.177	1.053	0.925	1.138
1969	1.192	1.128	0.957	1.179	1.076	0.948	1.134
1970	1.178	1.143	0.937	1.221	1.099	0.932	1.179
1971	1.307	1.220	1.008	1.210	1.166	1.006	1.160
1972	1.308	1.224	0.989	1.238	1.169	0.984	1.188
1973	1.321	1.130	0.928	1.217	1.076	0.932	1.155
1974	1.186	1.065	0.854	1.246	1.021	0.862	1.184
1975	1.250	1.080	0.872	1.239	1.024	0.876	1.169
1976	1.212	1.045	0.827	1.264	1.002	0.840	1.194
1977	1.317	1.121	0.881	1.273	1.077	0.899	1.199
1978	1.111	0.944	0.726	1.300	0.914	0.745	1.227
1979	1.203	1.007	0.787	1.279	0.964	0.806	1.196
1980	1.082	0.898	0.685	1.311	0.870	0.708	1.230
1981	1.169	0.996	0.758	1.315	0.954	0.776	1.230
1982	1.245	1.000	0.763	1.312	1.062	0.859	1.236
1983	1.159	1.067	0.792	1.347	1.024	0.812	1.260
1984	1.301	1.091	0.810	1.348	1.037	0.826	1.255
1985	1.403	1.157	0.858	1.349	1.092	0.872	1.253
1986	1.407	1.211	0.883	1.372	1.146	0.898	1.277
1987	1.451	1.305	0.942	1.385	1.229	0.953	1.289
1988	1.395	1.309	0.930	1.408	1.216	0.927	1.312
1989	1.337	1.265	0.886	1.427	1.184	0.889	1.332
1990	1.498	1.339	0.942	1.422	1.257	0.951	1.322
1991	1.509	1.391	0.967	1.438	1.290	0.964	1.338
1992	1.611	1.413	0.978	1.445	1.310	0.975	1.343
1993	1.536	1.361	0.934	1.458	1.261	0.931	1.355
1994	1.713	1.479	1.008	1.467	1.371	1.006	1.364
1995	1.440	1.373	0.927	1.480	1.279	0.928	1.377
1996	1.624	1.409	0.946	1.489	1.318	0.952	1.385

TT: Tornqvist-Theil TFP index

TFP: Unadjusted Malmqvist TFP index

Δ TE: Change in Technical Efficiency (unadjusted)

Tech Δ: Technical Change (unadjusted)

TFP*: Adjusted Malmqvist TFP index

Δ TE*: Change in Technical Efficiency (adjusted)

Tech Δ*: Technical Change (adjusted)

APPENDIX 2:

Nebraska Productivity Indexes

Year	TT	TFP	D TE	Tech D	TFP*	D TE*	Tech D*?
1960	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1961	0.964	1.011	0.951	1.062	1.031	0.959	1.075
1962	1.009	1.048	0.972	1.078	1.072	0.986	1.087
1963	1.011	1.010	0.911	1.109	0.962	0.882	1.090
1964	1.034	1.084	0.936	1.158	1.038	0.907	1.145
1965	1.056	1.087	0.942	1.154	1.037	0.916	1.132
1966	1.170	1.141	1.000	1.141	1.085	0.980	1.107
1967	1.175	1.089	0.924	1.179	1.042	0.908	1.148
1968	1.170	1.108	0.916	1.210	1.065	0.903	1.179
1969	1.264	1.169	0.987	1.184	1.110	0.974	1.139
1970	1.212	1.117	0.894	1.251	1.081	0.888	1.217
1971	1.307	1.165	0.939	1.240	1.118	0.935	1.196
1972	1.304	1.196	0.960	1.246	1.146	0.958	1.197
1973	1.273	1.068	0.855	1.249	1.023	0.856	1.195
1974	1.122	1.005	0.773	1.300	0.969	0.773	1.252
1975	1.285	1.114	0.872	1.278	1.039	0.853	1.218
1976	1.246	1.093	0.834	1.311	1.036	0.827	1.254
1977	1.422	1.156	0.889	1.301	1.079	0.874	1.234
1978	1.337	1.105	0.839	1.317	1.045	0.837	1.249
1979	1.394	1.120	0.833	1.345	1.079	0.844	1.278
1980	1.276	1.025	0.739	1.387	1.000	0.755	1.325
1981	1.475	1.157	0.840	1.377	1.098	0.839	1.308
1982	1.429	1.139	0.809	1.409	1.101	0.820	1.342
1983	1.292	1.213	0.829	1.463	1.195	0.850	1.406
1984	1.510	1.227	0.849	1.445	1.171	0.850	1.378
1985	1.674	1.340	0.919	1.458	1.269	0.914	1.390
1986	1.673	1.364	0.918	1.485	1.306	0.921	1.418
1987	1.723	1.509	0.993	1.519	1.457	1.000	1.457
1988	1.731	1.534	0.993	1.544	1.483	0.999	1.484
1989	1.769	1.515	0.968	1.566	1.472	0.977	1.507
1990	1.825	1.555	0.984	1.579	1.512	0.995	1.520
1991	1.907	1.586	0.993	1.598	1.531	0.994	1.540
1992	2.015	1.616	1.000	1.616	1.560	1.000	1.560
1993	1.881	1.583	0.963	1.644	1.519	0.954	1.592
1994	2.082	1.617	0.975	1.658	1.555	0.969	1.605
1995	1.875	1.596	0.949	1.683	1.549	0.948	1.634
1996	2.047	1.574	0.925	1.702	1.536	0.927	1.657

TT: Tornqvist-Theil TFP index

TFP: Unadjusted Malmqvist TFP index

Δ TE: Change in Technical Efficiency (unadjusted)

Tech Δ: Technical Change (unadjusted)

TFP*: Adjusted Malmqvist TFP index

Δ TE*: Change in Technical Efficiency (adjusted)

Tech Δ*: Technical Change (adjusted)

APPENDIX 2:

Oklahoma Productivity Indexes

Year	TT	TFP	D TE	Tech D	TFP*	D TE*	Tech D*?
1960	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1961	0.986	1.032	0.985	1.048	1.051	0.996	1.055
1962	0.891	0.992	0.891	1.113	0.971	0.881	1.101
1963	0.923	1.008	0.893	1.128	0.989	0.889	1.113
1964	1.018	1.051	0.931	1.130	1.031	0.932	1.107
1965	1.171	1.103	1.000	1.103	1.066	1.000	1.066
1966	1.043	1.057	0.908	1.165	1.035	0.910	1.137
1967	1.035	1.091	0.922	1.183	1.067	0.925	1.154
1968	1.115	1.101	0.936	1.176	1.066	0.938	1.137
1969	1.122	1.082	0.908	1.191	1.044	0.907	1.150
1970	1.143	1.153	0.932	1.237	1.119	0.931	1.202
1971	1.112	1.146	0.897	1.277	1.118	0.896	1.247
1972	1.189	1.226	0.951	1.288	1.182	0.942	1.254
1973	1.320	1.246	1.000	1.246	1.192	1.000	1.192
1974	1.304	1.231	0.954	1.291	1.187	0.955	1.243
1975	1.406	1.254	0.988	1.270	1.202	0.993	1.210
1976	1.313	1.172	0.912	1.285	1.126	0.921	1.223
1977	1.473	1.254	0.972	1.291	1.193	0.974	1.224
1978	1.242	1.057	0.816	1.296	1.000	0.816	1.225
1979	1.422	1.149	0.896	1.283	1.067	0.887	1.203
1980	1.340	1.136	0.854	1.330	1.067	0.848	1.257
1981	1.412	1.213	0.909	1.335	1.150	0.915	1.257
1982	1.649	1.328	1.000	1.328	1.244	1.000	1.244
1983	1.492	1.275	0.937	1.362	1.199	0.936	1.281
1984	1.497	1.273	0.936	1.361	1.200	0.941	1.275
1985	1.553	1.305	0.952	1.371	1.227	0.957	1.283
1986	1.594	1.390	1.000	1.390	1.302	1.000	1.302
1987	1.547	1.364	0.973	1.401	1.255	0.956	1.313
1988	1.546	1.350	0.965	1.400	1.243	0.952	1.306
1989	1.561	1.362	0.965	1.412	1.258	0.955	1.318
1990	1.524	1.302	0.920	1.415	1.207	0.916	1.318
1991	1.467	1.333	0.931	1.432	1.227	0.919	1.336
1992	1.525	1.285	0.895	1.435	1.198	0.897	1.336
1993	1.504	1.307	0.904	1.447	1.220	0.905	1.348
1994	1.585	1.458	1.000	1.458	1.349	0.993	1.359
1995	1.388	1.368	0.932	1.467	1.264	0.925	1.367
1996	1.432	1.388	0.942	1.473	1.296	0.945	1.372

TT: Tornqvist-Theil TFP index

TFP: Unadjusted Malmqvist TFP index

Δ TE: Change in Technical Efficiency (unadjusted)

Tech Δ: Technical Change (unadjusted)

TFP*: Adjusted Malmqvist TFP index

Δ TE*: Change in Technical Efficiency (adjusted)

Tech Δ*: Technical Change (adjusted)

APPENDIX 2:

South Dakota Productivity Indexes

	TT	TFP	D TE	Tech D	TFP*	D TE*	Tech D*
1960	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1961	0.958	1.028	0.951	1.081	1.047	0.951	1.100
1962	1.039	1.069	1.002	1.067	1.074	1.003	1.070
1963	1.043	1.055	0.970	1.088	1.052	0.966	1.089
1964	1.011	1.113	0.955	1.165	1.127	0.952	1.183
1965	1.080	1.131	0.995	1.136	1.131	0.998	1.133
1966	1.078	1.140	0.981	1.162	1.140	0.984	1.158
1967	1.153	1.174	1.011	1.161	1.165	1.014	1.148
1968	1.186	1.204	1.029	1.170	1.195	1.039	1.150
1969	1.117	1.113	0.945	1.178	1.099	0.955	1.150
1970	1.105	1.136	0.934	1.217	1.124	0.943	1.193
1971	1.220	1.210	1.002	1.208	1.185	1.012	1.171
1972	1.267	1.246	1.029	1.210	1.212	1.039	1.166
1973	1.201	1.177	0.949	1.241	1.153	0.964	1.196
1974	1.131	1.260	0.965	1.305	1.236	0.992	1.247
1975	1.131	1.171	0.914	1.282	1.192	0.968	1.231
1976	0.924	1.215	0.872	1.394	1.278	0.951	1.344
1977	1.260	1.260	0.980	1.286	1.266	1.038	1.220
1978	1.212	1.091	0.849	1.285	1.062	0.877	1.211
1979	1.203	1.063	0.821	1.295	1.037	0.853	1.216
1980	1.145	1.120	0.827	1.353	1.064	0.841	1.264
1981	1.269	1.191	0.885	1.345	1.192	0.945	1.262
1982	1.363	1.109	0.829	1.337	1.060	0.852	1.245
1983	1.227	1.123	0.811	1.384	1.116	0.861	1.297
1984	1.495	1.229	0.892	1.377	1.178	0.920	1.281
1985	1.486	1.229	0.879	1.399	1.187	0.913	1.300
1986	1.586	1.228	0.873	1.407	1.151	0.883	1.304
1987	1.600	1.339	0.929	1.441	1.289	0.962	1.339
1988	1.321	1.390	0.926	1.501	1.309	0.936	1.397
1989	1.606	1.542	1.029	1.498	1.443	1.039	1.389
1990	1.773	1.488	0.989	1.505	1.427	1.021	1.398
1991	1.799	1.524	0.999	1.526	1.473	1.039	1.418
1992	1.968	1.590	1.029	1.545	1.490	1.038	1.435
1993	1.684	1.419	0.904	1.569	1.328	0.910	1.460
1994	2.004	1.426	0.900	1.585	1.326	0.900	1.473
1995	1.640	1.301	0.808	1.611	1.239	0.826	1.500
1996	1.983	1.286	0.787	1.635	1.200	0.788	1.524

TT: Tornqvist-Theil TFP index

TFP: Unadjusted Malmqvist TFP index
Δ TE: Change in Technical Efficiency (unadjusted)
Tech Δ: Technical Change (unadjusted)

TFP*: Adjusted Malmqvist TFP index
Δ TE*: Change in Technical Efficiency (adjusted)
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