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Environmentally Adjusted Agricultural Productivity in the Great Plains

Jon P. Rezek and Richard K. Perrin

This study adjusts 1960–1996 agricultural productivity gains in a panel of Great Plains states to account for the discharge of pesticide and nitrogen effluents into the environment. The agricultural-environmental technology is approximated with translog distance functions that allow us to contrast traditional versus environmentally adjusted productivity gains. Findings indicate technical change has been increasingly biased toward environmentally friendly production. While the environmental adjustment reduced overall productivity gains during the sample period, in recent years adjusted productivity outpaced the traditional measure, reflecting the pro-environment bias in technical change.

Key words: agricultural productivity, distance function, environmental externalities, nitrogen, pesticides, technical change bias

Introduction

The productivity of agriculture in the United States has been studied vigorously. Measured performance rates in the vicinity of 2% 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 which do not account for such damage.

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 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 affecting our welfare. The inputs and outputs that are missing, including externalities such as environmental impacts, are those with no recorded transactions. Incorporating these goods and/or bads into

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productivity measures is difficult because we generally have no estimates of their quantities or 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 flow of environmental goods or bads, with appropriate welfare weights comparable to the prices 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 which 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 used calculated shadow prices from abatement costs to adjust a productivity index for a sample of pulp and paper mills. Färe et al. (1989) were the first to adjust productivity performance for environmental bads by explicitly including effluents as a component of the technology set for Pittman's data. They used data envelopment analysis (DEA) to estimate a nonparametric piecewise linear production set, reporting the environmentally adjusted efficiency of the mills. Alternatively, Färe et al. (1993) used a translog output distance function to represent this technology, estimated using the Aigner-Chu (1968) nonstochastic linear programming (LP) approach. Hailu and Veeman (2000) utilized this same approach to estimate an input distance function to measure pollution-adjusted productivity for the aggregate Canadian pulp and paper industry.

Several recent contributions have adjusted traditional agricultural productivity measures for the environmental impacts of production. Five of these studies have examined pesticide pollution, one looked at soil erosion, and one investigated nitrogen pollution. Most of these studies implicitly or explicitly weighted year-to-year changes in pollutants using shadow values of the pollutant, i.e., the opportunity cost of reducing pollutants in terms of the livestock and crop output foregone. Two of these analyses, however, weighted pollutant output with the difference between consumer willingness to pay and opportunity cost—a more satisfactory welfare concept, but one that is much more difficult to estimate.

All five pesticide studies used the Kellogg et al. (2002) estimates of the quantity of agricultural pesticide pollution, combined with the state-level agricultural input-output data described by Ball et al. (1999). The Kellogg et al. estimates are indexes of the relative toxicity of runoff waters and groundwater leaching, with four separate indexes to measure risk to humans, to fish, to algae, and to crustaceans. These data were developed from simulation models evaluated for each state and each year from 1960 through 1996. Their results show that raw quantities of pesticides applied in the United States (and this region) have declined or remained constant since the late 1970s, with risks to drinking water declining faster. The decline in pesticide risk combined with an increase in agricultural output would suggest a productivity advance. Indeed, all five studies estimated or implied downward revisions to productivity into the 1980s, but upward revisions thereafter, as pollution levels began to fall.

The first of these studies, Gollop and Swinand (1998), computed an adjusted productivity index for 1972–93 data by subtracting from a standard Tornqvist-Theil index the rate of change of pesticide pollution, weighted by the difference between its consumer value and producer shadow price. Gallop and Swinand used the results from a previous contingent valuation study of willingness to pay for clean water as their measure of consumer value, and estimated producers' shadow price using a cost function. The adjustment to the average annual productivity rate for the entire period was negligible, an increase from 1.47% to 1.48%. The second study, conducted by Ball, Färe et al. (2001), used a cost-indirect input distance function estimated with DEA to calculate Malmqvist-like productivity indexes both with and without pesticide pollution as a bad output. While they do not report average productivity rates for the United States, it can be inferred from their graphic summaries that including the two human-risk pesticide indexes reduced the average annual productivity rate from about 2.4% to −0.4% for the entire 1960–96 period.

In the third pesticide study, Ball, Lovell et al. (2001) also used DEA to calculate hyperbolic distance functions with and without all four Kellogg et al. pesticide indexes. Inclusion of these indexes reduced average annual productivity rates for the 1960–96 period from 1.54% to 0.98%. The fourth study, Färe, Grosskopf, and Weber (2001), used a quadratic directional output distance function, estimated with the Aigner-Chu approach, to provide an estimate of shadow prices of the bad outputs. The shadow value of the human risk indexes averaged 17.5% of the value of good output. Although the study did not calculate productivity rates, good outputs apparently increased at an average rate of 4.9%, bad outputs at a rate of 1.1%, and based on other studies using these data, inputs increased at a rate of about 3.4%. From these numbers it can be inferred that the average annual productivity gains for the 1960–96 period would be adjusted downward from about 1.5% to about 1.3%. Finally, in their 2002 analysis, Ball et al. used DEA to construct both a standard DEA Malmqvist productivity index and a separate quantity index for just the human risks as a "bad" output. Using the Färe, Grosskopf, and Weber (2001) estimate that these pollution outputs had an average shadow value equivalent to 17.5% of the good output value (see above), the implied average rate of productivity gain for 1960–96 would be reduced from 1.8% to 1.3%.

In addition to these five studies using the Kellogg et al. pesticide pollution indexes, Repetto et al. (1996) adjusted agricultural productivity from Ball's national-level data by including U.S. Department of Agriculture (USDA) estimates of changes in soil erosion between 1977 and 1992. They derived weights for this pollutant from an independent contingent valuation study of willingness to pay for clean water. The average productivity rate actually increased from 2.3% to 2.4% when the pollutant was included, due to declining soil erosion over the period.

Shaik and Perrin (1999) estimated reductions in Nebraska productivity due to both nitrogen and pesticide pollution. They developed independent estimates of productivity and pollution data for Nebraska agriculture from 1937–93, then used DEA to estimate hyperbolic Malmqvist productivity indexes. The unadjusted average productivity rate of 1.91% fell to 1.85% when nitrate pollution was included, to 1.27% when pesticide pollution was included, and to 0.0% when both were included. Shaik and Perrin estimated that productivity was reduced by these pollutants even as late as 1980–93, although the reduction then was smaller than during the heavy pollution period of 1960–80. A further report from this study (Shaik, Helmers, and Langemeier, 2002) estimates the shadow price of reducing a pound of nitrogen pollution to be from $0.44 early in the period to $4.25 in the 1990s.

In this study, we calculate Malmqvist agricultural productivity measures in four relatively homogeneous Great Plains states over the 1960–1996 period, decomposing the measure into its efficiency change, technical change, and scale change components as demonstrated by Orea (2002). These productivity measures are then adjusted to account for both nitrogen effluents and pesticide runoff in the region. While adjustment for pesticide pollution has considerable precedents, only one previous study in one state has considered the productivity implications of nitrogen effluent. Finally, we develop a measure of the pairwise bias of technical change over the period, which identifies the changing production-environment tradeoff in Great Plains agriculture.

The next section provides a description of the output distance function, the associated Malmqvist productivity index, its empirical decomposition, and the technical change bias measure. The data and empirical estimation procedures are then presented, after which we report and interpret both unadjusted and adjusted productivity measures as well as the bias measure. Conclusions are given in the final section.

The Theoretical Model

Output Distance Function

Consider a technology which utilizes a set of $\mathbf{x} \in \Re_+^N$ inputs to produce a set of $\mathbf{y} \in \Re_+^M$ outputs, of which $\mathbf{y}_d \in \Re_+^D$ are desirable and $\mathbf{y}_u \in \Re_+^U$ are undesirable. Let the output set, $P(\mathbf{x})$, 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, $D_O(\mathbf{x}, \mathbf{y})$, 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, θ, such that $\mathbf{y}/\theta$ remains in the feasible set:

$$D_O(\mathbf{x}, \mathbf{y}): \min\{\theta: \mathbf{y}/\theta \in P(\mathbf{x})\}. \tag{1}$$

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 $P(\mathbf{x})$. Values between 0 and 1 indicate production on the interior of the output set $P(\mathbf{x})$. 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 $\mathbf{x}$ and $\mathbf{y}$, and exhibits homogeneity of degree 1 in $\mathbf{y}$. It is assumed to be nondecreasing in $\mathbf{y}_d$ and nonincreasing in $\mathbf{y}_u$—i.e., 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 nonincreasing in $\mathbf{x}$. Finally, $D_O(\mathbf{x}, \mathbf{y})$ 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 does not require outputs to be freely disposable. Free disposability implies one or more outputs can be discarded without disrupting the feasibility of the remaining output combination. If each member of the output vector $\mathbf{y}'$ is less than or equal to the feasible output vector $\mathbf{y}$, then $\mathbf{y}'$ must be feasible as well. Mathematically, if $\mathbf{y}' \leq \mathbf{y} \in P(\mathbf{x})$, then $\mathbf{y}' \in P(\mathbf{x})$. However, for a given input set, it may not be possible to reduce effluents without sacrificing some of the desirable output. In the presence of detrimental outputs, an alternative assumption, weak output disposability, is more intuitively appealing. Weak output disposability assumes that a radial contraction of outputs is feasible with a given set of inputs. Specifically, if $\mathbf{y} \in P(\mathbf{x})$ and $\theta \in [0, 1]$, then $\theta\mathbf{y} \in P(\mathbf{x})$. The output distance function is compatible with weak output disposability.

Finally, Shephard (1970) shows that the derivatives of the parametric output distance function with respect to each of the outputs generate revenue-normalized shadow prices,

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

where p_i is the revenue-normalized 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 nonnegative—imposing the assumption that $D_O(\mathbf{x}, \mathbf{y})$ is nondecreasing in $\mathbf{y}_d$. Shadow prices of undesirable outputs are restricted to be nonpositive—imposing the alternative assumption that $D_O(\mathbf{x}, \mathbf{y})$ is nonincreasing in $\mathbf{y}_u$. These restrictions credit producers for increasing desirable output as well as reducing undesirables.

Productivity and the Rate and Environmental Bias of Technical Change

In this study, the distance function is used to represent the agricultural-environmental technology frontier for a panel of Great Plains states. Färe et al. (1994) showed that the output-distance function can be used to develop a Malmqvist productivity index (Caves, Christiansen, and Diewert, 1982) designated as:

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

where t_1 and t_2 are the two points in time under comparison. The Malmqvist index, M_O, is decomposed into the product of an index of efficiency change and index of technical change. The ratio outside the brackets is the index of Farrell efficiency, while the term within the brackets is the index of technical change.

Using the DEA approach of Färe et al. (1994), the indexes in (3) can be evaluated for each unit for any given pair of years, under the assumption that the technology is piecewise linear. In this analysis, the distance function is estimated parametrically with a translog specification and time as an argument. In this case, the comparable instantaneous productivity index can be calculated from the parametric counterpart of the Malmqvist index, given in Orea (2002), as:

$$\text{(4)} \qquad \ln(M_O) = \left[\ln\left(D_O(t+1)\right) - \ln\left(D_O(t)\right)\right] - \tfrac{1}{2}\left[\frac{\partial \ln\left(D_O(t+1)\right)}{\partial t} + \frac{\partial \ln\left(D_O(t)\right)}{\partial t}\right],$$

where the first term represents the efficiency change component, while the second represents the technical change component.

Orea notes, however, that the decomposition in equation (4) is not satisfactory because the resulting total factor productivity index does not exhibit the property of proportionality, which requires the index to be homogeneous of degree +1 in outputs and −1 in inputs. Proportionality only holds for $\ln(M_O)$ in the case of constant returns to scale: it thereby ignores the effects of scale economies on productivity change. Orea develops a parametric Malmqvist index which includes a scale effect term consistent with the proportionality property of a total factor productivity (TFP) index. Orea's index is given as:

$$\text{(5)} \qquad \ln(G_O) = \ln(M_O) + \tfrac{1}{2}\sum_{k=1}^{n}\left[\left(-\sum_{k=1}^{n}\frac{\partial \ln\left(D_O(t+1)\right)}{\partial \ln(x_k)}\right)\times e_k(t+1) + \left(-\sum\frac{\partial \ln\left(D_O(t)\right)}{\partial \ln(x_k)}\right)\times e_k(t)\right]\times \ln\left(\frac{x_k^{t+1}}{x_k^{t}}\right),$$

where

$$e_k(t) = \frac{\partial \ln\left(D_O(t)\right)/\partial \ln(x_k)}{\sum_{k=1}^{n}\partial \ln\left(D_O(t)\right)/\partial \ln(x_k)}.$$

In this equation, $\ln(M_O)$ is interpreted as in equation (4), while the remaining portion represents the contribution of changes in scale on productivity change. In the case of constant returns to scale or constant input quantities, this portion falls out and productivity change is simply attributed to efficiency change and technical change.

Finally, our parametric specification of the distance function permits us to measure the biases of technical change, as described by Fulginiti (2001). A measure of pairwise bias β_{ij}, defined as the percentage change in transformation elasticity between output y_i and output y_j for a given set of prices, can be directly measured from the estimated distance function. This measure of pairwise bias is written as:

(6) $$\beta_{ij} \equiv \left[\frac{\partial \left(\dfrac{\partial \ln(D_O) / \partial \ln(y_i)}{\partial \ln(D_O) / \partial \ln(y_j)} \right)}{\partial t} \right] \left[\frac{\partial \ln(D_O) / \partial \ln(y_j)}{\partial \ln(D_O) / \partial \ln(y_i)} \right].$$

This parameter measures the slope of the production frontier—i.e., the change in y_i per unit of y_j. Technical change is considered Hick-neutral if $\beta_{ij} = 0$, indicating a radial expansion of the output set, with no change in the transformation elasticity between outputs i and j. When y_i is a normal output and y_j an undesirable one, $\partial y_i/\partial y_j > 0$, $\beta_{ij} > 0$ implies that a greater amount of the normal output y_i must be given up to reduce the undesirable y_j by one unit.

Data and Empirical Estimation Procedures

In our empirical application, we consider the four Great Plains states of Kansas, Nebraska, Oklahoma, and South Dakota from 1960–1996. Basic data used for the study are the USDA's state-level productivity data series for two outputs (crops and livestock) and four inputs (land, labor, capital, and materials). Each of these indexes has a base value of 1.00 for 1987. To calibrate them for multilateral state comparisons, each index series was multiplied by the corresponding value reported for each state in the *1992 Census of Agriculture* (USDA, 1994). The census does not directly report the value of intermediate inputs, so we used the sum of values of seeds, fertilizers, chemicals, petroleum, electricity, feed, and purchased livestock. The resulting multilateral indexes are suitable for pooled analysis, yet retain the same data series as were used by USDA to construct the individual state productivity estimates with which we wish to compare our modified productivity estimates.[1]

Here, agricultural productivity is adjusted to account for the release of nitrogen and pesticides into the rural environment. Nitrogen is a major contaminant 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 surface water quality. We use *excess nitrogen*, computed using the National Research Council'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 tonnage of nitrogen added to the state's environment during a given year. It serves here as a measure of the nitrogen effluent produced by the agricultural sector (figure 1). In Kansas and Nebraska, excess nitrogen peaked in the late 1970s, while in Oklahoma it continued an upward trend throughout the period. In South Dakota it was insignificant throughout.

[1] The USDA data site (http://www.ers.usda.gov/data/agproductivity) offers a set of multilateral indexes for each state and component, relative to Alabama. These are constructed as the geometric mean of several binary Fisher indexes, the number of which varied from state to state and commodity to commodity. The Census calibration is more suitable for purposes of comparing our modified productivity indexes with the original USDA productivity indexes, because they are both clearly based on the same data series. (These data are further described in Ball, Batualt, and Nehring, 2001; for additional reference, see also Ahearn et al., 1998.) Our productivity indexes and output/input indexes for Kansas, Nebraska, Oklahoma, and South Dakota over the 1960–1996 period are found in appendices A and B, respectively.

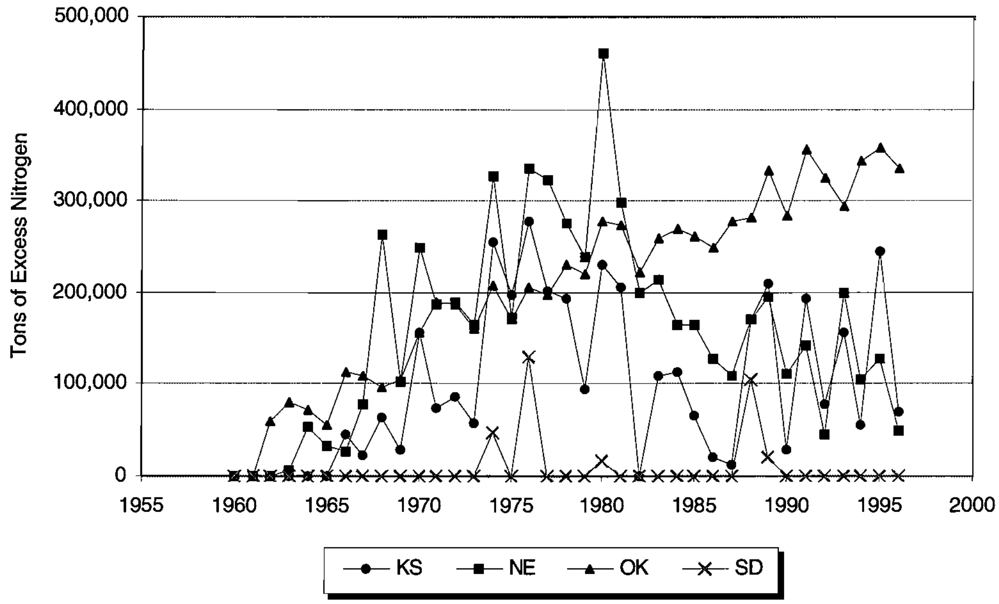

Figure 1. Excess nitrogen, NRC method: Kansas, Nebraska, Oklahoma, and South Dakota (1960–1996)

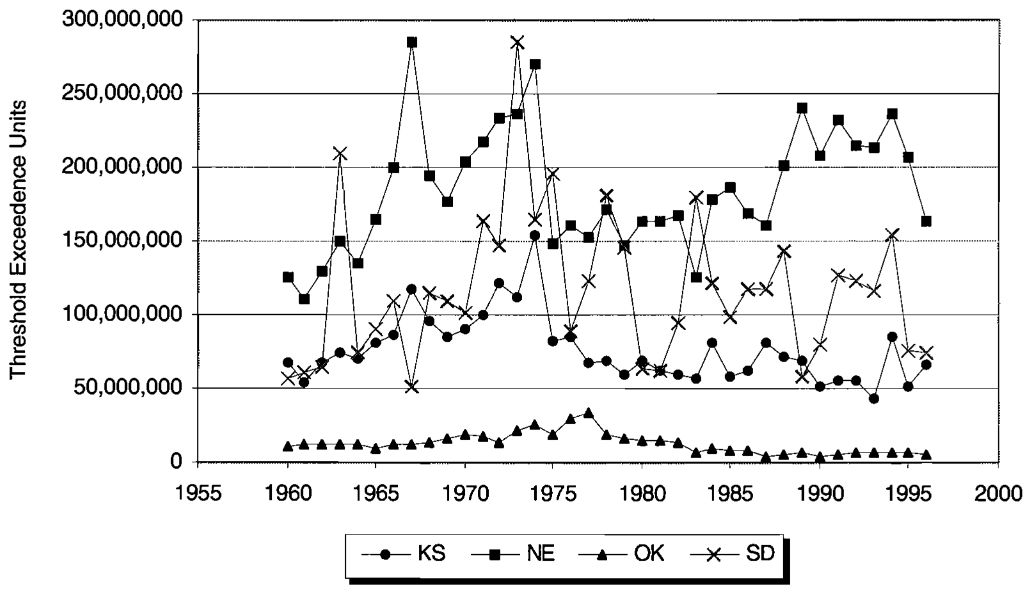

Figure 2. Kellogg pesticide runoff risk for drinking water: Kansas, Nebraska, Oklahoma, and South Dakota (1960–1996)

For our pesticide measure we use the Kellogg et al. (2002) series, "Pesticide Runoff Risk Indicators for Protection of Drinking Water," described earlier. This series is measured in millions of threshold exceedence units (TEUs), which are calculated as the difference between the annual simulated pesticide concentration and a given water quality threshold, summed across all affected areas (figure 2).

Our empirical approach is to estimate a translog distance function that, when evaluated at the appropriate data points, yields the year-to-year Malmqvist TFP index specified in equation (5). Our estimation procedure is the nonstochastic linear programming approach developed by Färe et al. (1993), which yields an enveloping technology frontier with all data points inside or on the frontier. 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; Swinton, 1998) and pulp and paper production (Hailu and Veeman, 2000), among others. The translog specification of the output distance function used here is:

$$(7) \qquad \ln\big(D_O(\mathbf{x},\mathbf{y})\big) = \alpha_0 + \sum_{i=1}^{M}\alpha_i \ln(y_i) + \sum_{j=1}^{N}\beta_j \ln(x_j) + \tfrac{1}{2}\sum_{i=1}^{M}\sum_{i'=1}^{M}\alpha_{ii'}\ln(y_i)\ln(y_{i'}) + \tfrac{1}{2}\sum_{j=1}^{N}\sum_{j'=1}^{N}\beta_{jj'}\ln(x_j)\ln(x_{j'}) + \sum_{i=1}^{M}\sum_{j=1}^{N}\gamma_{ij}\ln(y_i)\ln(x_j) + \mu_1 t + \tfrac{1}{2}\mu_2 t^2 + \sum_{i=1}^{M}\lambda_i \ln(y_i)t.$$

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

$$(8) \qquad \max_{\alpha,\beta,\gamma,\mu,\lambda} \sum_{t=1}^{T}\sum_{k=1}^{K}\ln\big(D_k^t(x^t, y^t)\big)$$

subject to:

$$(9) \qquad \ln(D(\mathbf{x},\mathbf{y})) \le 0,$$

$$(10) \qquad \partial\ln(D(\mathbf{x},\mathbf{y}))/\partial\ln(\mathbf{y}_d) \ge 0,$$

$$(11) \qquad \partial\ln(D(\mathbf{x},\mathbf{y}))/\partial\ln(\mathbf{y}_u) \le 0,$$

$$(12) \qquad \partial\ln(D(\mathbf{x},\mathbf{y}))/\partial\ln(\mathbf{x}) \le 0,$$

$$(13a) \qquad \sum_{i=1}^{M}\alpha_i = 1,$$

$$(13b) \qquad \sum_{i=1}^{M}\alpha_{ii} = 0, \quad \text{for } i = 1, \ldots, M,$$

(13c) $$\sum_{i=1}^{M} \gamma_{ij} = 0, \quad \text{for } j = 1, ..., N,$$

(14) $$\alpha_{ii'} = \alpha_{i'i}, \quad \beta_{jj'} = \beta_{j'j},$$

where the panel is T periods in length and consists of K cross-sections. Equation (9) requires that each observation remain in the feasible set. Equation (10) imposes nonnegative shadow prices on the desirable outputs, while equation (11) imposes nonpositive shadow prices on the undesirable outputs. Equation (12) imposes nonpositive shadow prices on inputs. Equations (13a)–(13c) impose homogeneity of degree 1 on outputs. Equation (14) requires the interaction parameters of the translog functional form to be symmetric. These restrictions are consistent with the theoretical 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 (8–10) and (12–14). This model does not include effluents in the analysis, and the results are used to calculate the traditional or unadjusted Malmqvist TFP index, shown in equation (5). We then run the linear program suggested by equations (8)–(14), this time incorporating the undesirables into the analysis, thereby adjusting the original baseline measure to account for both desirable and undesirable output production. The parameter results of both linear programs are displayed in table 1.

Empirical Results

Traditional Productivity Estimates

The empirical decomposition of the Malmqvist TFP measure for the entire sample period and various sub-periods is presented in panel A of table 2. The Malmqvist measure closely approximates the USDA's Tornqvist-Theil (TT) TFP measure for the states of Kansas and Oklahoma, but differs for Nebraska and South Dakota. Our Malmqvist measure of TFP growth in Kansas is 1.339% versus 1.342% using the TT approach. In Oklahoma, the comparable figures are 0.966% versus 0.982%; for Nebraska, 1.772% versus 1.95%; and for South Dakota, 0.933% versus 1.922%. The Malmqvist and TT indexes would provide the same measure of productivity growth if relative market prices reflect marginal rates of transformation and if the technology exhibits certain plausible characteristics as described in Caves, Christiansen, and Diewert (1982). These conditions may not be exactly met; therefore, estimates of the two measures may differ, but any systematic bias is not expected. The implication of the discrepancy in estimates for South Dakota, and to a lesser extent Nebraska, is that market prices of outputs relative to inputs have on average exceeded the ratio of their relative shadow prices as estimated by the gradients of the estimated technology. There is no obvious method to determine whether the substantial discrepancy between the two estimates here is the result of poor estimates of market prices, poor estimates of the technology gradients, or discrepancies between actual market prices and actual gradients.

As shown by table 2, panel A, the largest component of productivity growth is derived from changes in technology, which contributes on average about 1.15% per annum in the Great Plains states. Over the entire sample, technical change accounts for a 1.29%

Table 1. Parameter Values of the Unadjusted and Environmentally Adjusted Distance Functions

	Distance Function Value			Distance Function Value	
Parameter	Unadjusted	Adjusted	Parameter	Unadjusted	Adjusted
α_0	-57.89760	73.59964	γ_{11}	-0.27305	-0.27855
α_1	2.65715	0.97449	γ_{12}	0.27305	0.25574
α_2	-1.65715	0.24417	γ_{13}		0.00199
α_3		0.01571	γ_{14}		0.02083
α_4		-0.23436	γ_{21}	0.34503	0.41287
β_1	-2.82344	-3.22593	γ_{22}	-0.34503	-0.42445
β_2	-0.86786	-8.70255	γ_{23}		0.00011
β_3	0.00000	0.00000	γ_{24}		0.01147
β_4	11.02777	2.42690	γ_{31}	0.00000	0.00000
β_{11}	0.05854	0.54488	γ_{32}	0.00000	0.00000
β_{12}	0.16691	-0.11342	γ_{33}		0.00000
β_{13}	0.00000	0.00000	γ_{34}		0.00000
β_{14}	-0.04786	-0.20159	γ_{41}	-0.27941	-0.23753
β_{22}	0.57763	0.82501	γ_{42}	0.27941	0.25963
β_{23}	0.00000	0.00000	γ_{43}		-0.00340
β_{24}	-0.83631	-0.28811	γ_{44}		-0.01870
β_{33}	0.00000	0.00000	μ_1	-0.02599	-0.00881
β_{34}	0.00000	0.00000	μ_2	0.00037	-0.00022
β_{44}	0.23627	0.34685	λ_1	0.00655	0.00556
α_{11}	0.26886	0.33470	λ_2	-0.00655	-0.00505
α_{12}	-0.26886	-0.32953	λ_3		0.00004
α_{13}		-0.00038	λ_4		-0.00055
α_{14}		-0.00479			
α_{22}	0.26886	0.32764			
α_{23}		0.00020			
α_{24}		0.00169			
α_{33}		0.00000			
α_{34}		0.00018			
α_{44}		0.00292			

Notes: Subscripts on outputs correspond to the following: 1 = livestock, 2 = crops, 3 = excess nitrogen, and 4 = pesticide; for inputs, subscripts correspond to the following: 1 = capital, 2 = land, 3 = labor, and 4 = materials.

increase in productivity per year in Nebraska, 1.19% in Kansas, 1.13% in South Dakota, and 0.98% in Oklahoma. Technical change as measured here is a smooth phenomenon, as dictated by the construction of equation (7), and its rate of change is positive but declining over time. This trend is somewhat disconcerting because technical change is the most important long-term engine for growth in agricultural productivity.

The efficiency change we measure is characterized by dramatic reductions in efficiency during the 1970s, and equally dramatic increases in efficiency during the 1980s. The efficiency reductions in the 1970s offset technical change, resulting in reductions in productivity during that period. While the efficiency decline could be due to unfavorable weather during this period, a perusal of drought indexes for the area does not suggest

Table 2. Comparison of Unadjusted and Environmentally Adjusted Productivity Change and Components (percentage change)

		A. Unadjusted (%Δ)				B. Environmentally Adjusted (%Δ)			
State	Time Period	Efficiency	Technical	Scale	Productivity	Efficiency	Technical	Scale	Productivity
Kans.	1960–1972	-0.045	1.578	0.650	2.183	-0.159	0.701	0.028	0.570
	1973–1980	-4.009	1.288	0.996	-1.725	-2.826	0.902	0.010	-1.915
	1981–1987	4.338	1.080	-1.223	4.194	2.925	1.125	-0.049	4.002
	1988–1996	-0.549	0.684	0.583	0.717	-0.101	1.189	0.056	1.144
	1960–1996	**-0.200**	**1.193**	**0.346**	**1.339**	**-0.138**	**0.950**	**0.016**	**0.828**
Nebr.	1960–1972	-0.057	1.624	0.671	2.238	-0.306	0.748	0.086	0.529
	1973–1980	-2.552	1.404	1.043	-0.105	-1.363	1.040	-0.019	-0.341
	1981–1987	4.123	1.175	-1.172	4.126	2.914	1.229	-0.064	4.078
	1988–1996	-0.290	0.831	0.449	0.989	0.043	1.374	0.025	1.442
	1960–1996	**0.143**	**1.290**	**0.340**	**1.772**	**0.173**	**1.063**	**0.018**	**1.254**
Okla.	1960–1972	0.135	1.459	0.163	1.757	0.303	0.495	0.640	1.439
	1973–1980	-2.147	1.049	0.491	-0.607	-2.475	0.669	0.553	-1.253
	1981–1987	2.008	0.771	-0.556	2.222	2.309	0.786	-0.513	2.582
	1988–1996	-0.384	0.447	0.270	0.333	-0.518	0.907	0.171	0.559
	1960–1996	**-0.138**	**0.981**	**0.123**	**0.966**	**-0.130**	**0.693**	**0.279**	**0.843**
S. Dak.	1960–1972	0.305	1.381	0.020	1.706	0.629	0.671	0.222	1.521
	1973–1980	-2.522	1.069	-0.008	-1.460	-2.639	0.911	0.078	-1.650
	1981–1987	2.772	1.111	-0.019	3.863	2.702	1.338	-0.254	3.786
	1988–1996	-1.050	0.866	-0.067	-0.251	-0.972	1.530	-0.123	0.434
	1960–1996	**-0.182**	**1.130**	**-0.016**	**0.933**	**-0.094**	**1.069**	**0.011**	**0.985**

this factor could account for much of the explanation. Hailu 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 in the 1970s 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 are able to provide even more robust evidence of the inefficiency present in the late 1970s than the Hailu and Veeman work, reinforcing their observations.

The efficiency gains of the 1980s contribute several percentage points to productivity growth in all Great Plains states, making this the most productive period in the sample. Overall, productivity growth exceeded 4% per year in Kansas and Nebraska, and approached this rate in South Dakota (table 2, panel A). The farm financial crisis of that period may have contributed to these efficiency improvements by discouraging input use without reducing output commensurately. After 1987, there is again a distinct shift in efficiency patterns, with efficiency declines ranging from 0.29% to 1.05% contributing to reduced productivity gains. This is particularly evident in South Dakota, where inefficiency in this period is large enough to explain the gap between the TT and our Malmqvist measure of TFP.

The final component of the Malmqvist productivity index is the scale effect. Previous attempts to decompose productivity change using a distance function approach implicitly assume constant-returns-to-scale technology, thus setting scale change effects equal to zero. The work of Orea (2002) allows this component to be calculated directly. Two interesting observations are apparent from the results (table 2, panel A). First, Nebraska, Kansas, and to a lesser extent Oklahoma, have improved overall productivity through scale change, while South Dakota exhibits negligible scale effects. Second, for the three states exhibiting nontrivial scale effects, a similar temporal pattern emerges. Changes in scale boosted productivity approximately three quarters of a percent per year prior to 1980, with the largest scale effect occurring in the 1970s. In the subsequent period (1981–1987), while efficiency gains were substantial, change in scale had a drastic negative effect, reducing productivity by as much as 1.223% per year in Kansas and 1.172% in Nebraska. Finally, after 1987, the scale effect has once again led to productivity gains across these three states, albeit by smaller amounts than the pre-1980 changes.

Environmentally Adjusted Productivity Estimates

Panel B of table 2 reports the empirical decomposition of the environmentally adjusted Malmqvist productivity index for each state. When environmental variables were included in the analysis, annual productivity growth was revised downward from 1.34% to 0.83% in Kansas, from 1.77% to 1.25% in Nebraska, and from 0.97% to 0.84% in Oklahoma. Only South Dakota's productivity growth rate increased (from 0.93% to 0.99% per annum) when accounting for environmental outputs.

Disaggregating into sub-periods, however, reveals an underlying pro-environment trend. In the first sub-period, 1960–1972, productivity growth was revised downward substantially after accounting for negative agricultural externalities. This reduction was particularly sharp for Kansas and Nebraska, where growth was revised from over 2% annually to just over 0.5%. In the second and third sub-periods, productivity change was also revised downward, but the magnitude of the adjustment was far smaller. By the final sub-period, 1988–1996, environmentally adjusted productivity growth actually outpaced the traditional measure in all states (table 2, panel B).

The increasingly pro-environment shift is a product of a reduction in detrimental outputs relative to beneficial outputs. With the exception of Oklahoma, excess nitrogen per crop unit and per livestock unit peaked in the late 1970s. Similarly, pesticide pollution per unit of output peaked in the mid-1970s for all states and receded substantially by the end of the decade. Indeed, pesticide pollution itself, as measured by the Kellogg et al. (2002) study, has declined. There are several plausible factors which may contribute to this trend. First, certain organochlorine products such as DDT and aldrin, known for their persistence and toxicity, were banned in 1972, reducing pesticide risk. Over time, stricter regulation also resulted in the removal of other damaging pesticides from the market while encouraging safer biological versions. Modern pesticides persist in the environment for shorter periods and are generally less toxic than earlier variants, thus generating fewer health risks. In addition to the changing chemical properties of pesticides, the absolute quantity of active ingredients leveled off in the United States after peaking in 1982. A major portion of this trend is attributed to the replacement of organochlorine insecticides with alternatives which are applied more sparingly (Anderson and Magleby, 1997). The initiation and expansion of integrated pest management programs through state extension offices may have also contributed to the decline in pesticide pollution. Such programs are designed to encourage the use of environmentally friendly solutions to pest problems through biological and manual controls as well as precision pesticide application.

Excess nitrogen also declined relative to marketable outputs in three of the four states. This trend can be attributed to the constant or even decreased application rate for nitrogen on field crops evident in later years. Specifically, nitrogen use per acre of corn, the largest and most heavily fertilized crop in the region, declined after reaching a peak in the mid-1980s (Heimlich, 2003). Accompanying this change was an increase in amount of nitrogen-fixing soybean acreage planted in the region. Not coincidently, crop rotation—especially in a corn-soybeans-corn cycle, which has been shown to reduce the amount of nitrogen necessary to maintain yields—increased during the period (National Research Council, 1989). Finally, the real price of fertilizers declined until about 1987, but leveled off thereafter. While Denbaly and Vroomen (1993) show demand for nitrogen fertilizer to be highly price inelastic, price stabilization may have contributed marginally to decreased usage later in the period.

Several factors may have worked to reduce the growth rates of both nitrogen and pesticide pollution concurrently. Years of cumulative research on natural resource related issues, coupled with state extension service efforts to educate farm operators about the risks posed by agricultural chemicals and fertilizers, represent another plausible explanation for our results. Environmental legislation may have also played a role. The Clean Water Act of 1972 and the Safe Drinking Water Act of 1986 provided the impetus for state and federal programs designed to improve water quality conditions through regulation of agricultural and nonagricultural pollutants. The Conservation Reserve Program was initiated by Title XII of the Food Security Act in 1985 to reduce soil erosion on sensitive land. The primary benefit of retiring land of often marginal quality is a reduction in the pesticide and nitrogen runoff that is most likely to distort water quality.

In the first three columns of table 2, panel B, the computed environmentally adjusted productivity measures are decomposed into their component parts. After adjusting for environmental effluents, the average rate of technical change is lower than the traditional measure for three of the four states. But more significantly, technical change is rising through time, rather than falling as was the case for the unadjusted rates. By the final sub-period, rates of technical change with the inclusion of pesticides and nitrogen in the model are approximately 80% higher than traditional measures. Since technical change represents the largest source of long-term growth in agricultural productivity, these results can be viewed as a shift to more environmentally sustainable agriculture.

The same general patterns prevalent in the efficiency change component of the traditional Malmqvist productivity index are repeated in the adjusted model. Relatively small efficiency effects in the 1960–1972 period are followed by large reductions in efficiency from 1973–1980 (table 2, panel B). The substantial improvements in efficiency that occur in the 1981–1987 period are followed by a moderation of this trend after 1987. On the other hand, the inclusion of the environmental variables leads to rather large changes in the scale change component of the productivity measure. Whereas in the traditional model, average productivity improvements from scale change for Nebraska and Kansas were in excess of one-third of a percentage point, after adjusting for environmental variables these effects were negligible. South Dakota productivity growth from changes in scale was negligible in both analyses. Only Oklahoma exhibits any significant productivity improvement from scale change in the adjusted model (0.28%).

Environmental Bias

Another perspective from which to consider this trend is the bias of technical change. Table 3 reports the technical change biases, evaluated at average values for each state as represented in equation (6). The generally positive values in the first two columns

Table 3. Average Pairwise Biases of Technical Change

State	Livestock/ Nitrogen	Crops/ Nitrogen	Livestock/ Pesticide	Crops/ Pesticide
Kansas	0.023	0.003	-0.030	-0.051
Nebraska	0.025	0.004	-0.042	-0.063
Oklahoma	0.030	-0.018	-0.026	-0.074
South Dakota	0.095	0.071	-0.038	-0.062

indicate that, at the mid-point of the data, technical change was increasing the amount of livestock or crop production which must be given up to achieve a unit reduction in nitrogen pollution.[2] The negative values in the last two columns indicate that at the mid-point of the data, technical change was reducing the amount of livestock and crops which must be given up to reduce pesticide pollution. Thus in mid-period, 1978, technical changes were favorable for reducing pesticide pollution, but unfavorable for reducing nitrogen pollution. Further examination shows that the pace of the technical change bias for pesticide reduction declined over the sample period.

Conclusions

In this study, we have examined the agricultural productivity/environment tradeoff in a panel of four Great Plains states. The Aigner-Chu (1968) linear programming approach was used to estimate the production technology, including both good and bad outputs, specified as a translog output distance function. 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 as well as a Kellogg et al. (2002) measure of potential pesticide contamination.

Ignoring nitrogen and pesticide pollution, the standard Tornqvist-Theil index of average annual productivity gain was about 1.60% for the 1960–96 period, whereas the Malmqvist productivity index measure was approximately 1.25%. The Malmqvist technical change index, an estimate of the rate at which the production set itself expanded, yielded around 1.15%. 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 temporary inefficiencies.

When nitrogen and pesticide effluents are included, the average Malmqvist TFP change falls from about 1.25% to 0.98% per year, while the technical change component falls from about 1.15% to 0.94% per annum. Comparing year-by-year results, the adjusted productivity rates were substantially below the unadjusted rates prior to 1988, but afterward the pollution-adjusted rates began to exceed the standard rates. This turnaround reflects the nature of bias in the technological change, which was found at the mid-point of the period to be biased in favor of crops and livestock relative to pesticide pollution, though biased against crops and livestock relative to nitrogen pollution. These

[2] This conclusion is supported by Shaik, Helmers, and Langemeier (2002), who found shadow prices for reducing nitrogen pollution in Nebraska to be increasing during the entire period 1936–1997, including the 1970s.

biases represent the societal impacts of public and private 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 relative to harmful effluents.

By incorporating nitrogen and pesticide effluent into our production model we have 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.

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Appendix A. Productivity Indexes, 1960–1996

Kansas Productivity Indexes

Year	TT	TFP	Tech Δ	Eff Δ	Scale Δ	TFP*	Eff Δ*	Tech Δ*	Scale Δ *
1960	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1961	0.989	1.004	1.020	0.971	1.013	1.004	1.008	1.000	0.996
1962	0.968	0.987	1.038	0.951	0.999	0.994	1.015	0.982	0.997
1963	0.942	0.958	1.055	0.891	1.018	0.973	1.022	0.956	0.996
1964	0.982	0.994	1.072	0.932	0.995	1.014	1.028	0.989	0.997
1965	1.036	1.027	1.089	0.945	0.997	1.025	1.036	0.993	0.997
1966	0.988	0.988	1.107	0.878	1.017	0.894	1.043	0.860	0.997
1967	1.052	1.017	1.123	0.881	1.028	0.929	1.049	0.888	0.997
1968	1.120	1.072	1.141	0.912	1.031	0.961	1.056	0.912	0.997
1969	1.192	1.148	1.158	0.948	1.045	0.995	1.064	0.937	0.998
1970	1.178	1.123	1.175	0.913	1.047	0.969	1.072	0.905	0.998
1971	1.307	1.265	1.192	1.000	1.062	1.081	1.080	1.002	1.000
1972	1.308	1.299	1.208	0.995	1.081	1.071	1.088	0.981	1.003
1973	1.320	1.293	1.225	0.952	1.109	1.089	1.097	0.989	1.004
1974	1.184	1.116	1.242	0.830	1.083	0.971	1.106	0.874	1.005
1975	1.248	1.158	1.259	0.853	1.078	1.006	1.116	0.897	1.005
1976	1.209	1.167	1.276	0.825	1.109	0.990	1.126	0.877	1.003
1977	1.314	1.279	1.292	0.887	1.116	1.080	1.136	0.948	1.003
1978	1.108	1.128	1.308	0.751	1.148	0.909	1.147	0.789	1.004
1979	1.200	1.324	1.324	0.870	1.149	1.059	1.158	0.911	1.004
1980	1.080	1.132	1.340	0.722	1.171	0.919	1.169	0.783	1.004
1981	1.166	1.213	1.355	0.785	1.141	1.004	1.181	0.847	1.005
1982	1.242	1.318	1.371	0.838	1.148	1.199	1.194	1.000	1.004
1983	1.156	1.250	1.386	0.820	1.100	1.003	1.208	0.827	1.004
1984	1.297	1.333	1.401	0.852	1.117	1.074	1.221	0.876	1.004
1985	1.399	1.469	1.416	0.933	1.111	1.192	1.235	0.961	1.004
1986	1.402	1.473	1.431	0.934	1.103	1.185	1.250	0.944	1.004
1987	1.446	1.518	1.445	0.978	1.075	1.216	1.265	0.960	1.001
1988	1.391	1.407	1.457	0.906	1.066	1.126	1.279	0.881	0.999
1989	1.333	1.308	1.468	0.827	1.078	1.066	1.293	0.825	0.999
1990	1.493	1.550	1.478	0.959	1.093	1.268	1.308	0.967	1.002
1991	1.505	1.482	1.489	0.931	1.069	1.211	1.323	0.917	0.998
1992	1.606	1.596	1.500	0.970	1.097	1.312	1.339	0.978	1.002
1993	1.531	1.507	1.510	0.910	1.096	1.248	1.356	0.919	1.001
1994	1.711	1.685	1.520	1.000	1.108	1.380	1.373	1.002	1.003
1995	1.438	1.483	1.529	0.869	1.116	1.231	1.390	0.881	1.005
1996	1.621	1.619	1.536	0.931	1.133	1.347	1.408	0.952	1.006

TT: Tornqvist-Theil TFP index

TFP: Unadjusted Malmqvist TFP index

Eff Δ: Change in Technical Efficiency (unadjusted)

Tech Δ: Technical Change (unadjusted)

Scale Δ: Scale Change (unadjusted)

TFP*: Adjusted Malmqvist TFP index

Eff Δ*: Change in Technical Efficiency (adjusted)

Tech Δ*: Technical Change (adjusted)

Scale Δ*: Scale Change (adjusted)

Nebraska Productivity Indexes

Year	TT	TFP	Tech Δ	Eff Δ	Scale Δ	TFP*	Eff Δ*	Tech Δ*	Scale Δ *
1960	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1961	0.964	0.979	1.020	0.961	1.000	0.972	1.008	0.965	0.999
1962	1.008	1.023	1.038	0.981	1.004	1.010	1.016	0.995	0.999
1963	1.011	1.001	1.057	0.926	1.023	0.898	1.024	0.877	1.000
1964	1.034	1.027	1.074	0.948	1.008	0.922	1.030	0.897	0.998
1965	1.056	1.039	1.092	0.944	1.008	0.928	1.036	0.897	0.998
1966	1.170	1.154	1.110	1.011	1.029	0.993	1.044	0.949	1.003
1967	1.175	1.107	1.128	0.933	1.052	0.970	1.052	0.918	1.005
1968	1.170	1.113	1.145	0.923	1.053	0.955	1.059	0.896	1.006
1969	1.264	1.212	1.163	0.996	1.046	1.031	1.068	0.961	1.005
1970	1.211	1.141	1.181	0.902	1.071	0.957	1.076	0.882	1.008
1971	1.307	1.237	1.198	0.954	1.083	1.039	1.084	0.950	1.009
1972	1.304	1.308	1.215	0.993	1.084	1.066	1.094	0.964	1.010
1973	1.273	1.255	1.233	0.900	1.130	1.032	1.104	0.923	1.013
1974	1.121	1.089	1.251	0.783	1.113	0.930	1.115	0.824	1.013
1975	1.282	1.213	1.268	0.880	1.087	1.049	1.125	0.919	1.015
1976	1.244	1.210	1.286	0.850	1.107	1.028	1.137	0.893	1.012
1977	1.419	1.359	1.304	0.935	1.114	1.138	1.149	0.979	1.012
1978	1.334	1.385	1.323	0.929	1.126	1.118	1.162	0.953	1.009
1979	1.390	1.467	1.342	0.943	1.159	1.165	1.176	0.982	1.009
1980	1.272	1.297	1.360	0.810	1.178	1.037	1.189	0.864	1.009
1981	1.471	1.513	1.377	0.949	1.157	1.220	1.203	1.005	1.010
1982	1.425	1.479	1.395	0.914	1.160	1.176	1.217	0.957	1.009
1983	1.289	1.335	1.411	0.873	1.084	1.048	1.231	0.846	1.006
1984	1.506	1.517	1.426	0.947	1.124	1.225	1.246	0.977	1.007
1985	1.668	1.709	1.443	1.054	1.123	1.375	1.262	1.083	1.007
1986	1.667	1.696	1.461	1.044	1.112	1.354	1.279	1.052	1.006
1987	1.717	1.731	1.476	1.081	1.085	1.379	1.296	1.060	1.004
1988	1.725	1.716	1.490	1.061	1.085	1.365	1.312	1.036	1.004
1989	1.763	1.723	1.503	1.033	1.110	1.374	1.329	1.028	1.007
1990	1.818	1.825	1.517	1.083	1.111	1.460	1.346	1.077	1.007
1991	1.900	1.832	1.530	1.088	1.101	1.474	1.365	1.075	1.005
1992	2.007	1.903	1.543	1.109	1.112	1.544	1.384	1.109	1.006
1993	1.896	1.740	1.556	1.011	1.107	1.399	1.403	0.992	1.006
1994	2.050	1.906	1.568	1.091	1.114	1.560	1.424	1.090	1.005
1995	1.846	1.760	1.580	1.001	1.113	1.434	1.445	0.988	1.005
1996	2.016	1.893	1.591	1.053	1.130	1.571	1.466	1.064	1.007

TT: Tornqvist-Theil TFP index

TFP: Unadjusted Malmqvist TFP index

Eff Δ: Change in Technical Efficiency (unadjusted)

Tech Δ: Technical Change (unadjusted)

Scale Δ: Scale Change (unadjusted)

TFP*: Adjusted Malmqvist TFP index

Eff Δ*: Change in Technical Efficiency (adjusted)

Tech Δ*: Technical Change (adjusted)

Scale Δ*: Scale Change (adjusted)

Oklahoma Productivity Indexes

Year	TT	TFP	Tech Δ	Eff Δ	Scale Δ	TFP*	Eff Δ*	Tech Δ*	Scale Δ *
1960	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1961	0.988	1.036	1.019	1.017	0.999	1.042	1.007	1.035	1.000
1962	0.893	1.004	1.037	0.971	0.997	0.987	1.012	0.973	1.002
1963	0.924	1.018	1.053	0.971	0.995	1.002	1.016	0.978	1.008
1964	1.020	1.057	1.070	0.993	0.995	1.040	1.021	1.009	1.010
1965	1.173	1.102	1.087	1.021	0.993	1.083	1.026	1.037	1.018
1966	1.046	1.056	1.104	0.963	0.993	1.038	1.031	0.980	1.028
1967	1.034	1.095	1.120	0.986	0.993	1.081	1.036	1.018	1.025
1968	1.121	1.099	1.135	0.973	0.995	1.077	1.041	1.000	1.035
1969	1.128	1.081	1.151	0.939	1.000	1.047	1.047	0.953	1.050
1970	1.149	1.154	1.166	0.988	1.002	1.115	1.052	1.004	1.055
1971	1.119	1.156	1.179	0.972	1.009	1.122	1.057	0.998	1.064
1972	1.196	1.235	1.191	1.016	1.020	1.188	1.061	1.037	1.080
1973	1.325	1.278	1.204	1.021	1.039	1.214	1.067	1.037	1.097
1974	1.312	1.255	1.218	0.992	1.039	1.196	1.073	1.015	1.098
1975	1.412	1.268	1.230	1.005	1.026	1.205	1.079	1.029	1.085
1976	1.319	1.184	1.244	0.929	1.025	1.119	1.086	0.950	1.084
1977	1.479	1.274	1.256	0.978	1.037	1.185	1.094	0.985	1.100
1978	1.247	1.085	1.269	0.823	1.039	1.004	1.102	0.825	1.105
1979	1.427	1.224	1.283	0.906	1.053	1.113	1.111	0.892	1.123
1980	1.344	1.176	1.296	0.856	1.061	1.075	1.120	0.851	1.129
1981	1.411	1.241	1.307	0.917	1.036	1.155	1.128	0.928	1.103
1982	1.646	1.360	1.319	1.004	1.028	1.273	1.137	1.024	1.093
1983	1.489	1.294	1.330	0.955	1.019	1.203	1.146	0.967	1.085
1984	1.494	1.307	1.340	0.958	1.018	1.219	1.155	0.977	1.081
1985	1.551	1.338	1.350	0.974	1.018	1.256	1.164	0.999	1.080
1986	1.591	1.412	1.359	1.021	1.018	1.318	1.174	1.037	1.083
1987	1.544	1.374	1.367	0.985	1.020	1.288	1.183	1.000	1.089
1988	1.542	1.385	1.376	0.985	1.021	1.290	1.193	0.991	1.091
1989	1.557	1.388	1.384	0.975	1.029	1.296	1.203	0.982	1.097
1990	1.521	1.350	1.392	0.942	1.030	1.285	1.214	0.964	1.097
1991	1.462	1.363	1.400	0.950	1.025	1.271	1.225	0.947	1.096
1992	1.520	1.328	1.406	0.917	1.030	1.257	1.237	0.930	1.093
1993	1.499	1.343	1.413	0.922	1.030	1.275	1.249	0.934	1.093
1994	1.580	1.484	1.418	1.004	1.042	1.406	1.261	1.009	1.106
1995	1.380	1.397	1.422	0.936	1.050	1.317	1.272	0.929	1.114
1996	1.424	1.416	1.424	0.952	1.045	1.355	1.284	0.954	1.106

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Tech Δ*: Technical Change (adjusted)

Scale Δ*: Scale Change (adjusted)

South Dakota Productivity Indexes

Year	TT	TFP	Tech Δ	Eff Δ	Scale Δ	TFP*	Eff Δ*	Tech Δ*	Scale Δ *
1960	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1961	0.958	0.997	1.017	0.981	1.000	1.001	1.006	0.993	1.002
1962	1.039	1.061	1.032	1.028	0.999	1.057	1.011	1.039	1.005
1963	1.043	1.068	1.048	1.019	1.000	1.051	1.018	1.015	1.017
1964	1.011	1.073	1.063	1.010	0.999	1.072	1.024	1.032	1.015
1965	1.081	1.098	1.077	1.021	0.999	1.089	1.029	1.045	1.012
1966	1.079	1.107	1.092	1.015	0.999	1.094	1.036	1.039	1.017
1967	1.154	1.156	1.107	1.042	1.002	1.145	1.042	1.069	1.027
1968	1.187	1.175	1.122	1.046	1.002	1.159	1.050	1.078	1.024
1969	1.118	1.106	1.137	0.971	1.002	1.086	1.058	0.999	1.027
1970	1.106	1.095	1.151	0.949	1.002	1.076	1.066	0.983	1.027
1971	1.221	1.187	1.165	1.015	1.004	1.159	1.074	1.045	1.032
1972	1.268	1.227	1.180	1.037	1.002	1.200	1.084	1.078	1.027
1973	1.203	1.197	1.195	0.994	1.008	1.147	1.094	1.004	1.044
1974	1.132	1.173	1.208	0.967	1.004	1.135	1.102	0.999	1.031
1975	1.130	1.082	1.220	0.884	1.003	1.068	1.111	0.939	1.023
1976	0.926	1.038	1.230	0.844	1.000	1.052	1.119	0.932	1.009
1977	1.262	1.178	1.241	0.948	1.001	1.170	1.127	1.020	1.018
1978	1.214	1.135	1.256	0.903	1.001	1.095	1.140	0.931	1.032
1979	1.205	1.142	1.272	0.898	1.001	1.103	1.153	0.924	1.035
1980	1.146	1.092	1.286	0.848	1.002	1.052	1.166	0.873	1.033
1981	1.270	1.192	1.299	0.917	1.000	1.180	1.178	0.977	1.026
1982	1.364	1.220	1.314	0.928	1.000	1.185	1.193	0.963	1.031
1983	1.227	1.221	1.329	0.921	0.997	1.145	1.209	0.927	1.022
1984	1.496	1.321	1.343	0.985	0.999	1.286	1.225	1.024	1.025
1985	1.487	1.336	1.359	0.985	0.999	1.299	1.243	1.020	1.025
1986	1.586	1.319	1.374	0.960	1.000	1.294	1.261	1.008	1.018
1987	1.601	1.431	1.390	1.029	1.000	1.371	1.280	1.055	1.015
1988	1.323	1.275	1.401	0.911	0.999	1.169	1.296	0.893	1.009
1989	1.607	1.402	1.411	0.996	0.998	1.367	1.311	1.054	0.990
1990	1.774	1.484	1.423	1.046	0.997	1.436	1.329	1.078	1.002
1991	1.799	1.499	1.436	1.046	0.998	1.451	1.349	1.078	0.997
1992	1.969	1.511	1.449	1.046	0.997	1.477	1.371	1.078	0.999
1993	1.685	1.331	1.461	0.912	0.998	1.282	1.394	0.924	0.995
1994	1.999	1.458	1.475	0.993	0.996	1.452	1.418	1.025	0.999
1995	1.636	1.325	1.488	0.894	0.995	1.294	1.443	0.893	1.004
1996	1.978	1.399	1.502	0.937	0.994	1.426	1.469	0.967	1.004

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Appendix B. Output and Input Indexes, 1960–1996

OUTPUT INDEXES

	Livestock Output				Crop Output			
Year	**KS**	**NE**	**OK**	**SD**	**KS**	**NE**	**OK**	**SD**
1960	2,774,473	2,423,163	1,402,822	1,570,390	1,344,754	1,074,015	568,668	467,172
1961	3,368,539	2,616,054	1,499,009	1,720,920	1,206,284	921,031	510,473	367,503
1962	3,424,469	2,757,450	1,511,788	1,783,042	1,064,526	976,552	394,057	443,379
1963	3,727,239	2,908,394	1,583,413	1,886,776	972,060	960,650	406,422	457,273
1964	3,640,801	3,078,607	1,658,450	2,028,182	976,005	861,827	449,078	357,870
1965	3,439,681	2,997,103	1,766,550	1,955,294	1,159,542	931,827	587,231	435,256
1966	3,793,122	3,246,829	1,827,702	2,029,061	1,030,766	1,188,942	466,341	427,171
1967	3,842,162	3,434,150	1,876,301	2,155,404	1,142,770	1,126,092	456,380	495,969
1968	3,911,260	3,573,310	1,955,060	2,143,700	1,279,498	1,086,041	536,534	515,102
1969	4,175,773	3,418,664	2,049,920	2,010,995	1,451,537	1,330,385	549,482	508,053
1970	4,485,685	3,862,834	2,275,768	2,066,617	1,308,020	1,131,683	500,062	455,355
1971	4,840,238	3,946,257	2,388,603	2,190,533	1,613,735	1,365,270	439,135	563,891
1972	5,404,445	4,021,530	2,654,220	2,149,828	1,632,452	1,499,444	482,329	605,165
1973	4,967,795	3,940,381	2,806,751	2,298,311	1,854,005	1,614,541	712,180	594,027
1974	4,359,101	3,694,436	2,840,668	2,371,172	1,456,346	1,225,354	577,443	446,860
1975	4,189,072	3,444,657	2,651,466	2,019,449	1,600,255	1,503,797	664,707	496,008
1976	4,669,004	3,758,565	2,479,194	2,028,950	1,630,190	1,483,599	601,406	256,402
1977	5,096,459	3,812,077	2,795,482	2,056,928	1,826,958	1,867,985	705,082	633,209
1978	5,037,993	3,896,690	2,381,305	1,998,097	1,602,005	1,969,615	625,084	714,976
1979	4,971,429	4,496,879	2,677,683	1,971,782	2,078,136	2,142,157	863,905	758,682
1980	4,876,726	4,568,184	2,861,494	2,147,406	1,714,871	1,811,899	671,040	588,189
1981	4,816,580	4,417,886	2,770,530	2,108,947	1,822,287	2,265,451	681,753	735,516
1982	4,796,211	4,615,671	2,829,531	1,970,233	2,125,611	2,144,962	820,740	895,044
1983	4,959,417	4,606,818	2,702,529	2,070,806	1,723,935	1,533,813	619,895	711,213
1984	5,002,401	4,428,326	2,662,420	2,074,381	1,980,607	2,160,005	687,539	951,409
1985	5,033,487	4,716,879	2,720,098	2,092,654	2,283,792	2,521,992	703,727	952,294
1986	5,400,348	4,763,586	2,926,086	1,863,652	2,148,700	2,402,085	669,054	1,001,767
1987	5,436,076	5,164,678	2,882,935	2,102,687	2,114,896	2,187,112	632,895	950,147
1988	5,491,300	5,320,261	2,843,841	2,180,290	1,782,808	2,090,916	740,561	530,916
1989	5,579,840	5,602,190	2,941,170	2,170,889	1,547,874	2,133,800	725,646	752,745
1990	5,801,350	5,615,193	2,815,971	2,187,931	2,201,642	2,403,083	789,856	988,254
1991	5,711,309	5,454,735	2,874,605	2,173,155	1,918,868	2,421,437	673,110	995,468
1992	6,045,388	5,558,208	2,783,832	2,170,659	2,270,577	2,651,484	778,813	1,072,895
1993	5,845,086	5,618,376	2,843,082	1,921,600	2,080,676	2,127,067	722,901	863,655
1994	6,407,307	5,397,904	3,273,109	1,921,090	2,456,845	2,787,224	708,284	1,251,455
1995	6,439,350	5,666,657	3,146,041	1,886,653	1,854,552	2,177,674	579,637	992,829
1996	6,517,772	5,472,480	3,159,864	1,780,580	2,348,069	2,831,078	607,587	1,341,070

Livestock is calculated as: $V_t = V_{1992}(S_t/S_{1992})$
where V_t = value of livestock in year t,
S_t is USDA livestock index for year t,
S_{1992} is USDA livestock index for 1992,
V_{1992} is the value of livestock from the 1992 Census of Agriculture.

Crops are calculated as: $V_t = V_{1992}(C_t/C_{1992})$
where V_t = value of crops in year t,
C_t is USDA crop index for year t,
C_{1992} is USDA crop index for 1992,
V_{1992} is the value of crops from the 1992 Census of Agriculture.

INPUT INDEXES

	Capital Input Index				Land Input Index			
Year	**KS**	**NE**	**OK**	**SD**	**KS**	**NE**	**OK**	**SD**
1960	3,651,052	3,144,011	2,004,385	2,569,027	25,290,528	24,725,296	18,513,661	13,731,864
1961	3,681,710	3,150,535	1,983,874	2,583,911	24,039,083	22,981,808	18,236,550	13,259,892
1962	3,682,324	3,131,645	1,965,742	2,542,305	23,463,025	22,728,678	17,653,281	13,109,995
1963	3,695,476	3,180,013	1,958,083	2,572,452	23,761,921	23,132,140	17,756,331	13,166,020
1964	3,707,798	3,201,415	1,963,520	2,608,266	23,433,080	22,353,973	17,754,455	13,082,434
1965	3,740,236	3,218,776	1,990,398	2,584,945	23,301,637	22,311,798	17,671,870	12,893,394
1966	3,878,305	3,319,855	2,023,652	2,630,066	23,140,416	21,795,681	17,539,411	12,725,201
1967	3,951,896	3,491,097	2,050,842	2,676,952	24,436,481	23,643,282	18,023,129	13,267,273
1968	4,086,681	3,615,174	2,111,452	2,758,964	23,969,337	22,666,531	17,927,821	12,873,803
1969	4,197,999	3,682,619	2,170,897	2,817,309	22,906,267	22,400,254	17,338,196	12,615,311
1970	4,291,968	3,791,656	2,201,184	2,814,774	22,521,645	22,348,764	17,032,124	12,550,099
1971	4,333,035	3,770,982	2,183,893	2,815,956	22,907,538	23,137,017	17,333,395	12,946,298
1972	4,374,320	3,833,317	2,198,585	2,822,802	21,870,814	22,051,516	16,776,796	12,425,191
1973	4,396,547	3,897,555	2,216,883	2,843,539	24,113,977	24,177,237	17,818,061	13,152,946
1974	4,642,024	4,074,014	2,359,273	2,939,202	24,642,342	25,023,576	18,012,033	13,575,155
1975	4,752,317	4,093,897	2,488,046	2,942,084	24,481,685	24,886,531	17,319,624	13,538,957
1976	4,900,845	4,242,208	2,533,068	2,985,754	24,423,649	24,854,368	17,211,109	13,472,253
1977	5,042,897	4,380,095	2,558,798	2,894,864	24,315,456	24,771,402	17,054,683	13,436,977
1978	5,116,106	4,549,796	2,632,453	3,061,594	23,071,544	23,610,937	16,580,734	13,017,713
1979	5,178,246	4,523,685	2,649,372	3,041,209	23,133,251	23,925,200	16,433,230	13,103,281
1980	5,366,119	4,833,220	2,764,985	3,216,969	24,265,797	24,633,957	16,847,284	13,368,016
1981	5,238,308	4,753,788	2,693,462	3,152,105	24,272,715	24,605,513	16,555,477	13,259,323
1982	5,018,478	4,637,951	2,668,430	3,068,371	23,762,929	23,960,295	16,040,344	13,015,848
1983	4,951,480	4,615,230	2,603,625	3,041,791	21,403,880	20,673,562	14,486,318	11,730,749
1984	4,827,859	4,504,967	2,534,760	2,954,132	22,496,468	23,508,576	14,986,958	12,733,466
1985	4,738,486	4,449,575	2,489,197	2,924,504	22,438,471	23,393,040	15,044,018	12,627,560
1986	4,506,362	4,098,581	2,379,811	2,685,626	21,591,063	22,579,980	14,852,210	12,339,524
1987	4,300,877	3,817,567	2,298,930	2,562,578	20,762,536	21,441,718	14,534,596	11,899,118
1988	4,082,843	3,679,497	2,221,662	2,501,049	20,538,274	21,473,084	14,505,059	11,819,203
1989	3,972,882	3,757,997	2,188,167	2,411,764	21,293,661	22,368,277	15,160,234	12,193,357
1990	3,869,153	3,598,084	2,190,633	2,388,783	21,441,315	22,255,673	15,274,367	12,071,355
1991	3,843,863	3,667,994	2,197,970	2,418,152	21,057,097	22,422,840	14,674,431	12,007,242
1992	3,713,712	3,549,159	2,134,331	2,398,312	21,724,808	22,712,646	15,753,961	12,263,928
1993	3,682,764	3,496,376	2,104,917	2,393,972	21,821,365	22,316,099	15,751,581	11,866,434
1994	3,592,548	3,366,269	2,065,217	2,363,482	22,055,243	23,112,582	15,836,866	12,298,438
1995	3,578,503	3,353,144	2,085,855	2,372,385	22,064,690	22,749,235	15,884,049	12,251,090
1996	3,476,863	3,251,260	2,064,476	2,309,109	22,608,252	23,308,750	16,201,376	12,495,409

Capital is calculated as: $V_t = V_{1992}(K_t/K_{1992})$
where V_t = value of capital in year t,
K_t is USDA capital index for year t,
K_{1992} is USDA capital index for 1992,
V_{1992} is the value of machinery and equipment from the 1992 Census.

Land is calculated as: $V_t = V_{1992}(D_t/D_{1992})$
where V_t = value of land in year t,
D_t is USDA land index for year t,
D_{1992} is USDA land index for 1992,
V_{1992} is the value of land and buildings from the 1992 Census.

***INPUT INDEXES* (cont.)**

	Labor Input Index				**Materials Input Index**			
Year	**KS**	**NE**	**OK**	**SD**	**KS**	**NE**	**OK**	**SD**
1960	576,913	499,098	301,102	207,008	2,686,749	2,459,288	1,085,139	1,251,436
1961	540,820	470,612	290,129	194,384	3,043,554	2,610,854	1,098,230	1,290,831
1962	528,822	458,542	274,270	192,752	2,908,497	2,706,746	1,126,264	1,338,658
1963	510,023	421,831	262,148	186,426	3,125,090	2,927,848	1,177,505	1,463,217
1964	498,757	399,400	235,537	175,773	2,856,865	2,806,056	1,195,548	1,435,452
1965	492,226	394,609	231,325	170,859	2,901,981	2,813,430	1,268,803	1,422,722
1966	477,912	372,138	232,598	169,527	3,169,031	3,198,646	1,361,272	1,469,059
1967	446,060	351,704	249,969	162,854	3,155,970	3,219,525	1,320,931	1,549,906
1968	418,932	338,036	237,325	157,454	3,237,810	3,354,106	1,407,880	1,515,715
1969	387,899	330,096	236,110	156,858	3,615,769	3,288,265	1,567,139	1,568,165
1970	379,783	322,503	242,526	146,509	3,708,827	3,677,690	1,614,822	1,570,779
1971	385,165	328,370	240,441	144,066	3,858,735	3,694,941	1,710,135	1,612,742
1972	383,129	346,708	248,151	137,654	4,493,695	3,992,496	1,858,179	1,576,639
1973	401,860	355,007	249,548	153,075	4,280,174	4,184,275	2,038,810	1,776,127
1974	375,295	400,751	191,168	169,190	3,716,045	3,694,394	1,966,600	1,579,431
1975	360,090	404,680	198,073	162,731	3,663,327	3,330,751	1,771,684	1,498,241
1976	392,803	421,222	190,295	153,545	4,156,893	3,652,516	1,752,384	1,369,335
1977	389,716	366,805	165,764	170,132	4,279,320	3,783,890	1,957,585	1,463,745
1978	371,832	403,766	179,541	153,871	5,272,305	4,400,269	2,015,324	1,764,997
1979	435,631	396,239	166,695	166,166	5,247,312	5,011,679	2,325,546	1,805,669
1980	468,498	418,802	153,480	169,536	5,159,360	5,062,461	2,343,209	1,744,299
1981	489,502	394,585	180,200	186,146	4,634,825	4,650,520	2,007,259	1,642,783
1982	445,173	391,098	138,121	149,248	4,989,749	5,008,671	1,897,758	1,820,595
1983	448,417	346,915	129,805	188,441	5,087,545	4,970,490	1,912,792	1,846,572
1984	337,754	378,301	169,164	149,004	4,945,315	4,518,653	1,857,771	1,741,730
1985	372,048	393,828	155,138	157,722	4,849,018	4,564,362	1,861,463	1,758,837
1986	331,201	352,529	144,343	126,367	5,166,284	4,710,529	1,944,565	1,658,316
1987	317,513	331,588	126,741	141,593	5,024,064	4,724,014	2,079,814	1,715,673
1988	283,534	327,925	157,198	135,910	5,016,690	4,744,774	2,163,740	1,657,205
1989	300,632	332,248	150,628	140,356	4,936,938	4,815,020	2,202,286	1,449,760
1990	322,313	343,448	170,376	126,244	5,258,232	4,961,942	2,193,930	1,645,379
1991	275,050	316,429	166,911	133,591	4,892,288	4,592,346	2,224,652	1,545,434
1992	264,795	272,476	170,116	106,624	5,243,050	4,730,899	2,145,853	1,541,124
1993	268,585	227,548	168,943	102,214	5,170,669	4,830,452	2,166,406	1,549,433
1994	258,008	269,414	157,779	112,407	5,358,787	4,620,810	2,371,087	1,537,453
1995	311,655	269,536	176,135	121,876	5,532,329	4,779,994	2,455,146	1,675,528
1996	284,579	283,361	182,013	117,325	5,631,988	4,899,082	2,361,588	1,622,256

Labor is calculated as: $V_t = V_{1992}(L_t/L_{1992})$

where V_t = value of labor in year t,

L_t is USDA labor index for year t,

L_{1992} is USDA labor index for 1992,

V_{1992} is hired and contract labor from the 1992 Census.

Intermediate Inputs is calculated as: $V_t = V_{1992}(I_t/I_{1992})$

where V_t = value of intermediate inputs in year t,

I_t is USDA intermediate input index for year t,

I_{1992} is USDA intermediate input index for 1992,

V_{1992} is the value of seeds, fertilizers, chemicals, petroleum, electricity, purchased livestock and feed from the 1992 Census.