Agricultural Productivity and Environmental Impacts: The Role of Non-parametric Analysis

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Abstract

Our contribution in this article is to compare two methods of adjusting agricultural productivity estimates for the effects of bad environmental outputs. One method is a direct non-parametric Malmquist index with the environmental variables include. The other method is to use the shadow prices from the Malmquist analysis to modify a Tornqvist-Theil with shadow shares for the environmental variables.

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Saleem Shaik and Richard Perrin

Since agriculture is potentially an important contributor to environmental degradation, it may be especially important in agriculture to adjust productivity measures to reflect environmental impacts. Measurement of productivity is important, but it is not an unambiguous task, especially when un-priced (or poorly-priced) inputs or outputs are involved. While the empirical difficulty of measuring appropriate environmental variables is in itself a daunting challenge, a similarly vexing problem is that of identifying appropriate weights for these variables, relative to conventional inputs and outputs. Consumer willingness to pay would be the most appropriate concept of value for constructing these weights, but production shadow prices are often more feasible to evaluate, since they may be measured from production-related information alone. Production shadow prices can be used to evaluate the opportunity cost of reducing environmental impacts in terms of other outputs that must be foregone. This paper employs non-parametric analysis to adjust agricultural productivity measurements for environmental impacts in the state of Nebraska, 1936-1997. The study quantifies two environmental damage variables, potential environmental nitrate pollution and potential environmental pesticide impact, and utilizes their shadow prices to construct adjusted productivity indexes.

Recent years have seen growing importance of non-parametric approaches in the computation of agriculture productivity (especially the Malmquist productivity index) and environmental impacts. This is because the approach imposes no explicit a priori functional form, it requires no price information, it accommodates multiple output and input technology under both weak and strong disposability, and finally, it allows the recovery of shadow prices of poorly priced or un-priced goods.

There is a useful equivalency between the Malmquist productivity index and the commonly used Tornqvist-Theil (TT) productivity index. Caves, Christensen and Diewert (CCD) in 1982 established that when technologies are represented by certain functional forms, a Tornqvist-Theil index computed with shadow shares calculated from the Malmquist shadow prices provides the same productivity measure as the CCD version of the Malmquist. The two indexes will not necessarily be equivalent when the technology is represented by the piece-wise linear relationship of the data envelopment analysis (DEA) approach, however, because data points on the vertexes of the frontier have no unique tangent hyperplane. Furthermore, the CCD approach implies one particular method of projecting inefficient observations to the frontier, whereas alternative projections such as the hyperbolic used here may project a particular inefficient observation to a different facet of the frontier. Since the CCD Malmquist index and the TT index calculated with Malmquist shadow prices may differ, our purpose in this article is to compare them as alternative methods of adjusting traditional productivity indexes for environmental impacts.

In this paper we use DEA to estimate direct hyperbolic graph measures of environmentally-adjusted productivity gains at various levels of commodity aggregation and, alternatively, use the gradients of environmental variables from these analyses to adjust the standard TT index. In general, we find that the direct productivity measures result in very little, if any, measurable productivity gain over the period, whereas the indirect shadow price measures result in productivity gains that are only slightly smaller than traditional measures, and in some cases exceed them.

The rest of the paper is organized as follows. We describe the procedures for calculating TT productivity indexes and for adjusting them for environmental outputs. We then describe Fare's direct hyperbolic graph measure of environmentally-adjusted productivity change, and the method of recovering the gradients to be used as weights in an adjusted TT index. Next we describe the Nebraska agriculture data set, and finally we report the empirical results.

The Tornqvist-Theil index of productivity change

First consider the index approach to measuring productivity change. Denote inputs by the vector $x = (x_1, \ldots\ldots, x_n)$ and outputs by $y = (y_1, \ldots\ldots, y_m)$, with corresponding price vectors $w = (w_1, \ldots\ldots, w_n)$ and $p = (p_1, \ldots\ldots, p_n)$. The Tornqvist-Theil index of productivity change between year *t* and year *T* is the share-weighted logarithmic change in outputs minus the share-weighted logarithmic change in inputs (average revenue shares for outputs and average cost shares for outputs), or

$$(1) \qquad \ln TFP_{T,t} = \sum\nolimits_j \tfrac{1}{2}\left(RS_{j,T} + RS_{j,t}\right) \ln \frac{y_{j,T}}{y_{j,t}} - \sum\nolimits_j \tfrac{1}{2}\left(CS_{i,T} + CS_{i,t}\right) \ln \frac{x_{i,T}}{x_{i,t}}$$

where $RS_{j,t}$ is the share of output *j* in year *t* revenue and $CS_{i,t}$ is the share of input *i* in year *t* costs. This and related index measures have a theoretical basis as a proxy for consumer welfare, but they also owe much to Solow residual concept - residual output changes that are not accounted for by changes in inputs must be due to technical progress. Further discussion of these antecedent ideas can be found in Antle and Capalbo and in Caves, Christensen and Diewert.

Typical applications of productivity indexes do not include non-market inputs or outputs such as polluting emissions or other environmental impacts. There is no conceptual problem in doing so. A flow of chemicals into surface waters, for example, could be included as an undesirable output with a negative price reflecting its marginal disutility to recipients of the externality, or equivalently as an input with a positive price[1]. As a practical matter, not only are the quantities of such flows more difficult to measure than market goods (there are no markets in which to monitor quantities), the value that should be attached to them is even more difficult to measure. Since these values are not directly observable, they are often referred to as shadow prices.

There are two distinct notions of shadow prices that have been considered in environmental accounting efforts. One notion is the value of the marginal disutility to the recipients of the non-market output(s), or consumers' shadow price, which can be thought of as the slope of a consumer's indifference curve between the non-market output and purchasable goods. If the purpose of the productivity index is to measure progress in terms of human welfare, this is the appropriate shadow price for productivity measurement (Smith, 1998), but it is measureable only with heroic assumptions. An alternative notion is the opportunity cost of increasing or decreasing the non-market output, or production shadow price, which can be thought of as the slope of a production possibilities curve for the non-market output versus other outputs. Under perfect markets, the consumer and producer shadow prices are equal, but for the non-market outputs we are considering that is unlikely. Production shadow prices are measurable from estimation of production technologies (Färe and Grosskopf, 1998), and in the present study we will utilize such production shadow prices to adjust productivity measurements for environmental impacts.

Non-parametric graph productivity indexes and shadow prices

The past decade has witnessed a surge in the application of non-parametric techniques to productivity measurement, much of which is summarized by Lovell (1996). In general these methods are distance function approaches that compare the production plans that were available at time *T* with those that were available at time *t*. The productivity change over the interval is typically measured as the proportional increase in output that was achievable at *T* from year *T* inputs, relative to what would have been achievable at *t* from year *T* inputs[2]. Implicit in the estimation procedure is estimation of the piece-wise linear convex production hull that envelops the set of production plans available at either point in time. The production shadow prices of environmental outputs are measured as the relevant gradients of this production technology, an issue considered further below.

The particular non-parametric productivity measure considered here is one of Färe's hyperbolic graph productivity measures described in Färe, Grosskopf and Lovell, Chapter 8 section 3. In this approach, productivity gain between time *t* and time *T* is the proportion by which good outputs could have been increased, and "bad" outputs and inputs simultaneously decreased, in year *T* as compared to year *t*. To formally represent this measure, first partition the output vector into good outputs and bad outputs, $y = (y_g, y_b)$ and define the technology using the graph reference set satisfying constant returns to scale, strong disposability of good outputs and weak disposability of bad outputs:

$$(2) \qquad GR^T = \left\{ \begin{array}{l} (x, y_g, y_b) : x \text{ can produce } (y_g, y_b) \text{ in year } T \\ 0 \le \theta \le 1 \text{ implies } \theta(x, y_g, y_b) \in GR^T \quad y_b' < y_b \Rightarrow \theta(x, y_g, y_b') \in GR^T \end{array} \right\}$$

A direct measure of productivity gain from year *t* to *T* can then be derived from the hyperbolic graph distance function, or its equivalent linearized programming problem:

$$(3) \qquad H^T(x^t, y_g^t, y_b^t)^{-1} = \max_{\theta, z} \left\{ \theta : \left(\theta^{-1} x^t, \theta y_g^t, \theta^{-1} y_b^t\right) \in GR^T\left(x^t\right) \right\}$$

$$or$$

$$\begin{array}{llll} \max\limits_{\theta, z} \theta \;\; s.t. & \theta y_g^t \le Y_g z & \text{where} & Y_g = \left(y_g^1, y_g^2, \ldots\ldots\ldots, y_g^T\right) \\ & (2 - \theta) y_b^t = Y_b z & & Y_b = \left(y_b^1, y_b^2, \ldots\ldots\ldots, y_b^T\right) \\ & (2 - \theta) x^t \ge X z & & X = \left(x^1, x^2, \ldots\ldots\ldots, x^T\right) \\ & z \ge 0 & & \end{array}$$

Thus, examining the year *t* production plan compared with the production possibilities revealed to be available through some future year T, a solution value of θ=1.2 would indicate that 20% more good outputs could be produced with 20% less bad outputs and 20% less inputs than were observed in year *t*. Hence the interpretation is that the productivity increase between year *t* and year *T* was $(.20)^2$ =0.04, or 4%.

Estimation of the above productivity measure includes estimation of the piecewise linear technology available at time *T*, with the estimated facets consisting of linear combinations of previously observed production plans. For a particular year *t*, the optimal values of *z* represent the linear combination of other years' plans that identify the frontier production facet to which the year *t* production point is projected (along a hyperbolic arc identified by $\left(\theta^{-1} x^t, \theta y_g^t, \theta^{-1} y_b^t\right)$. The producer shadow price of a bad output y_{b_k}, in terms of a good output y_{g_j} that must be given up, is the gradient of the technology frontier facet at the relevant point. That gradient is measured as the ratio of the shadow prices of the constraint row for the bad output and the constraint row for the good output, or

$$(4) \qquad r_{b_k,g_j} = \frac{\lambda_{y_{b_k}}}{\lambda_{y_{g_j}}}$$

where λ_k is the dual value of row *k* in the programming solution above

Observations that form the vertexes of the year *T* technology hull will have multiple values of the shadow prices, while observations interior to the hull are projected to various facets of the hull with different shadow prices.

In the study reported here, a single good output is measured as a Tornqvist-Theil index. To convert a shadow price from units of index per unit of bad output to dollars per unit of bad output, we multiply the above-defined shadow price by the value of output for the year in question. These prices we then use to calculate shadow shares to modify Tornqvist-Theil productivity indexes as an alternative to the direct non-parametric productivity indexes derived from the programming approach.

Output, Input and Environmental Data

Nebraska agriculture sector data span a period of 62 years from 1936-97. The details of the methodology and sources of data used in the construction of output, input and environmental damage variables are presented in Shaik (1998.) The traditional outputs included are food grains, feed crops, vegetable and oil crops, meat animals, poultry and other livestock including milk, honey and wool production. An single aggregate Tornqvist-Theil output index was constructed using prices farmers received to calculate shares for the TT weights.

Traditional inputs considered were farm equipment, breeding livestock capital stock, farm real estate, farm labor and intermediate inputs. A single aggregate Tornqvist-Theil input index was constructed, calculating shares from implicit rental values for farm equipment and breeding livestock, cash rents for farm land, wage compensation rates for labor, and expenditures on intermediate inputs.

We used the concept of nitrogen surplus as a proxy for environmental nitrate production due to agriculture. Nitrogen surplus is calculated as the difference between nitrogen inputs [commercial fertilizer, animal manure and legume fixation] and nitrogen removed by harvested crops. Exner and Spalding, 1990, and Muller *et al.*, 1995, report evidence based on sampling of wells in Nebraska of a positive correlation between high levels of nitrate contamination in irrigation wells and fertilizer and animal manure accumulation in the soil. This offers some support for using nitrogen surplus as a proxy for potential environmental nitrate production due to agriculture.

USDA, Soil Conservation Service publishes a pesticide leaching loss potential (PLLP) for each pesticide based on the solubility (mg/L), persistence (half life days) and sorption (K_{oc} ml/g) of the pesticides. For the average of Nebraska soil variations, individual chemicals were coded 1, 2, 3 and 4 for large, medium, small and extra small pesticide leaching loss potential. A 1 indicates higher pesticide leaching to groundwater with high solubility, high half life and low sorption values, while a 4 indicates a lower pesticide leaching to groundwater with low solubility, low half life and high sorption. An index of pesticide leaching loss potential was calculated for all the pesticides for each survey year by using by using pounds of pesticide applied as shares. A time series PLLP index was computed by interpolation between the survey years. Deflating total pounds of pesticides applied by the PLLP index gives potential environmental pesticide damage index.

Results for Nebraska agriculture

Several productivity indexes for Nebraska agriculture were computed using SHAZAM (1997): the traditional Tornqvist-Theil total factor productivity (TT-TFP), the non-parametric graph total factor productivity (G-TFP), the non-parametric graph environmental-adjusted productivity (G-EAP) and the environmental-adjusted Tornqvist-Theil productivity (TT-EAP). The annual growth rates of the variables used in the computation of the productivity measures is presented in Table 1.

TABLE 1. ANNUAL GROWTH RATES[1] OF AGGREGATE OUTPUT, INPUT AND ENVIRONMENTAL DAMAGE VARIABLES, 1936-1997

Variables	Average Annual Growth Rate
Aggregate Output	2.710
Aggregate Input	1.523
Total Factor Productivity	1.168
Potential Environmental Nitrate Pollution	2.079
Potential Environmental Pesticide Impact	8.287

[1] Average annual growth rate is computed as: $[(X_{t+1}/X_t)^{1/T} - 1]*100$ where X is input or output variable and T is the total time period.

The first comparison to be made is between the two traditional productivity measures. The two indexes are reported in Table 3 and graphed in Figures 2 and 3. The TT-TFP productivity index reached a value of 2.055 by 1997, for an average annual productivity gain of 1.168%. The G-TFP productivity index reached 1.739, for an average gain of only 0.897%, slightly more than three-fourth the rate estimated by the TT-TFP.

When we added nitrogen surplus to the input and output variables, the G-EAP_N measure of productivity gain dropped only about four percent, from 0.90%/year to 0.86%/year. When we instead added the pesticide variable, the G-EAP_P measure dropped by two-thirds, to 0.32%/year. Adding both environmental variables, measured productivity gain disappears, indicating that the rate of increase in the nitrogen surplus and the pesticide variable has been so much faster than the rate of output growth that no productivity gains can be detected. This result reveals one of the difficulties in non-parametric productivity analysis: an input (or bad output in this case) with trivial starting base may increase at a much faster rate than output, and when this occurs no productivity gain at all may be detected. If the input has trivial value as well, a TT index would appropriately ignore it, as opposed to its very significant impact on a non-parametric productivity analysis. Here, of course, both the pesticide and nitrogen levels start near zero and the pesticide growth rate is four times that of output. This of course does not tell us the value of the pesticide variable, it merely indicates that it will likely dominate the productivity measurement.

The non-parametric analysis provides us with estimates of the producer shadow prices of the two environmental bad, in terms of index units of output given up per unit of the bad reduced. For nitrogen the ratio of dual values is in index units of output given up per million pounds of nitrogen surplus reduced (average: 0.324), or we can convert to current dollars worth of output given up per pound of nitrogen surplus reduced (average: $3.084/lb N.) The comparable shadow prices for pesticides are 0.033 index units per thousand pounds of toxicity-adjusted pesticide, or $.217/lb. When both environmental variables are included, the shadow price for N falls by about half, but at for pesticides remains about the same.

Using these shadow prices, we calculated the environmental-adjusted TT indexes reported in Table 3. Here we see that the addition of nitrogen surplus alone reduced measured productivity gains by nine percent to 1.07%/year, pesticides alone reduced measured gains not at all, and the two environmental variables together reduced measured gains by nearly forty percent, to 0.74%per year.

The non-parametric analysis is also represented graphically in Figures 1a and 1b. Here we normalize both output and the environmental bad (nitrate and pesticide) by the input index, so that the shadow prices for the environment are clearly seen as the gradients of the piece-wise linear technology representation. In Figure 1a, only the two positive sloped segments are relevant, as all data points are projected on a hyperbolic arc to those facets (data points to the left of the vertical axis are projected up and to the right, whereas others are projected up and to the left.) Similarly in Figure 1b, also only two positive sloped segments are relevant. Due to the piecewise linear non-parametric approximation the shadow shares influence of the outcome of the shadow prices as well as the productivity measures.

The annual growth rate of non-parametric graph Malmquist EAP measures is 0.897 (traditional total factor productivity), 0.860 (potential environmental nitrate pollution) and 0.311 (potential environmental pesticide impact), lower than the traditional and modified Tornqvist-Theil EAP measures of 1.168, 1.102 and 1.168 respectively. The annual growth rate of TT-TFP and G-TFP measures prior to 1980 is higher compared to TT-EAP and G-EAP growth rate respectively indicating that it has been over estimated. The TT-TPF and G-TFP growth rate for the period after 1980 was under estimated compared to TT-EAP and G-EAP growth rate respectively.

The environmentally adjusted productivity measures would be less than the non-parametric graph productivity measures, which seems consistent with the notion that accounting for environmental damage lowers productivity. In contrast the modified Tornqvist-Theil productivity measures indicate higher or equal productivity change between 1936-97. The results confirm that the traditional Tornqvist-Theil total factor productivity measure overestimate/underestimate productivity growth if environmental cost/benefits are accounted.

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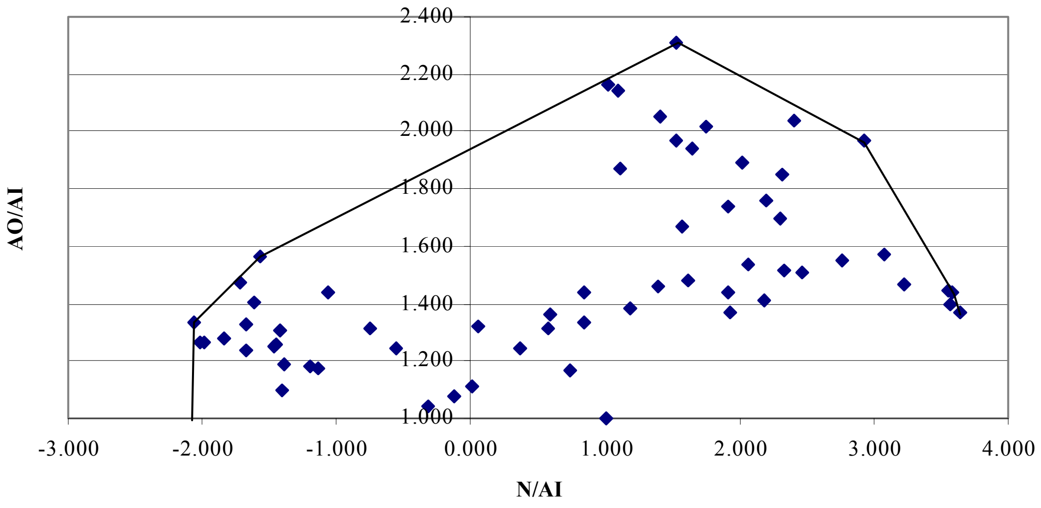
Figure 1a. Figure 1b. Output index, Nitrate index, Pesticide index normalized by input index, 1936-1997

Outputs (index) and Nitrate (index and not Mil lbs)



Outputs (index) and Pesticide (index and not Mil lbs)

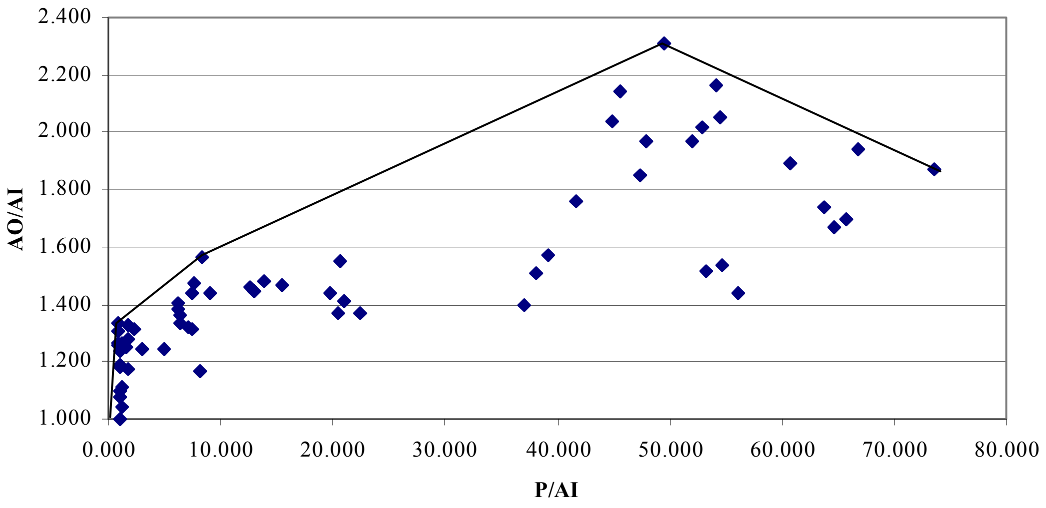


Figure 2. Nebraska Agriculture Sector Traditional (TFP) and Environmental Adjusted (EAP) Tornqvist-Theil Measures, 1936-1997

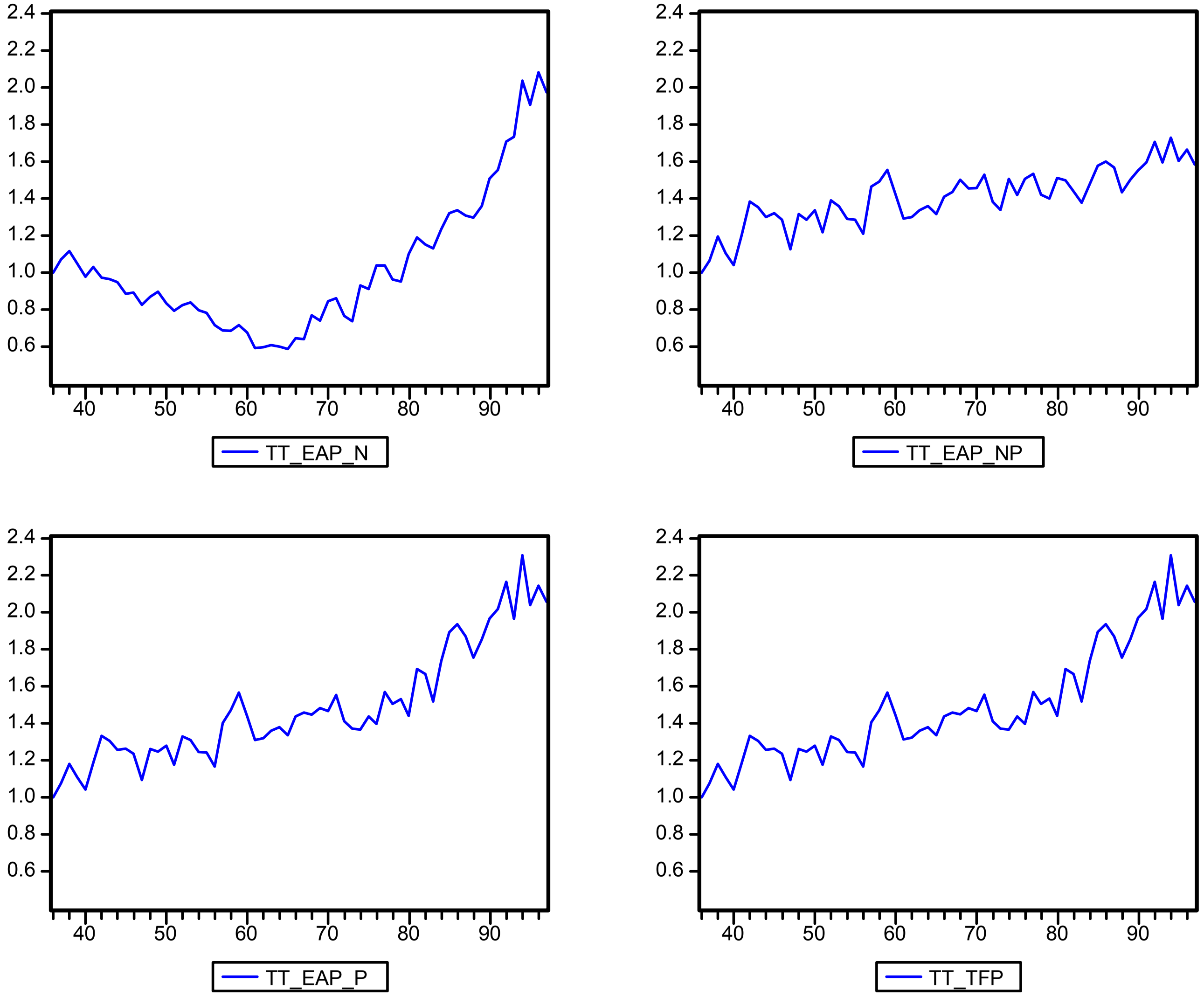


FIGURE 3. NEBRASKA AGRICULTURE SECTOR GAAPH MALMQUIST (GTFP) AND ENVIRONMENTAL ADJUSTED (EAP) GRAPH MALMQUIST MEASURES, 1936-1997

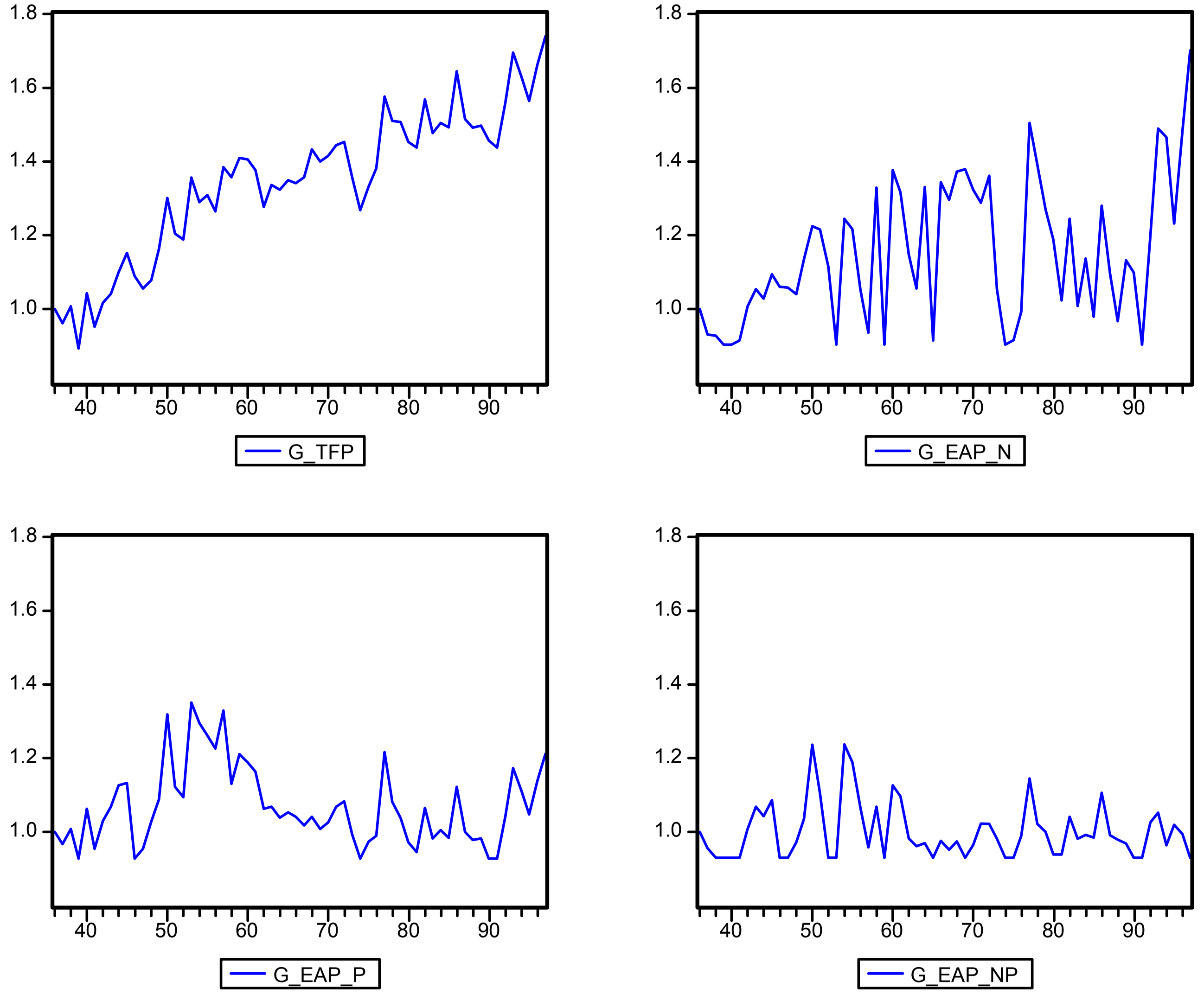


TABLE 2. RATIO OF DUAL LP SLOPES AND SHADOW PRICE OF ENVIRONMENTAL DAMAGE

Time Periods	**Nitrate EAP_N**	**Pesticide EAP_P**	**Nitrate EAP_NP**	**Pesticide EAP_NP**
	Ratio of Dual LP Slopes			
1936-50	0.315	0.089	0.069	0.107
1951-60	0.307	0.022	0.102	0.022
1961-70	0.350	0.017	0.059	0.022
1971-80	0.492	0.013	0.339	0.009
1981-90	0.241	0.013	0.261	0.015
1991-97	0.205	0.011	0.233	0.006
1936-97	0.324	0.033	0.166	0.037
1936-80	0.360	0.041	0.134	0.047
1980-97	0.227	0.012	0.250	0.011
	Shadow Prices ($ / per total bads)			
1936-50	1.546	0.410	0.257	0.406
1951-60	2.037	0.146	0.655	0.144
1961-70	2.302	0.110	0.381	0.142
1971-80	6.378	0.156	4.662	0.100
1981-90	3.642	0.190	3.926	0.226
1991-97	3.492	0.183	3.947	0.098
1936-97	3.084	0.217	2.060	0.208
1936-80	2.897	0.228	1.352	0.221
1980-97	3.580	0.187	3.935	0.173

Units of shadow prices are $/ lb Nitrogen and $/ lb pesticide.

TABLE 3. NEBRASKA AGRICULTURE SECTOR TORNQVIST-THEIL AND GRAPH MALMQUIST INDEXES OF TRADITIONAL AND ENVIRONMENTAL ADJUSTED PRODUCTIVITY MEASURES FOR POTENTIAL NITRATE AND PESTICIDE CONTAMINATION

Year	Tornqvist-Theil Index				Graph Malmquist Index			
	TT-TFP	**TT-EAP_N**	**TT-EAP_P**	**TT-EAP_NP**	**G-TFP**	**G-EAP_N**	**G-EAP_P**	**G-EAP_NP**
1936	1	1	1	1	1	1	1	1
1940	1.042	0.978	1.042	1.040	1.043	0.904	1.063	0.930
1950	1.281	0.834	1.281	1.337	1.301	1.225	1.319	1.236
1960	1.439	0.676	1.438	1.419	1.406	1.376	1.188	1.126
1970	1.466	0.845	1.465	1.457	1.415	1.324	1.026	0.965
1980	1.439	1.099	1.439	1.510	1.453	1.188	0.972	0.939
1981	1.694	1.192	1.694	1.499	1.438	1.024	0.945	0.939
1982	1.666	1.150	1.665	1.438	1.568	1.245	1.065	1.042
1983	1.518	1.130	1.517	1.376	1.477	1.009	0.983	0.982
1984	1.736	1.232	1.735	1.478	1.505	1.137	1.005	0.992
1985	1.893	1.321	1.892	1.577	1.493	0.979	0.984	0.985
1986	1.937	1.337	1.936	1.600	1.644	1.280	1.122	1.106
1987	1.870	1.308	1.869	1.567	1.515	1.097	1.000	0.991
1988	1.756	1.297	1.756	1.433	1.492	0.967	0.978	0.979
1989	1.853	1.359	1.853	1.501	1.498	1.132	0.983	0.969
1990	1.968	1.509	1.967	1.550	1.458	1.099	0.928	0.930
1991	2.019	1.555	2.019	1.595	1.437	0.904	0.928	0.930
1992	2.163	1.707	2.163	1.706	1.560	1.199	1.043	1.026
1993	1.965	1.734	1.965	1.596	1.695	1.489	1.173	1.052
1994	2.308	2.037	2.308	1.728	1.630	1.466	1.112	0.964
1995	2.040	1.906	2.040	1.601	1.564	1.232	1.047	1.019
1996	2.142	2.082	2.142	1.664	1.663	1.482	1.139	0.994
1997	2.055	1.973	2.055	1.583	1.739	1.701	1.212	0.930

Where TT-TFP (TT-EAP) and G-TFP (G-EAP) are the Tornqvist-Theil and Graph Malmquist total factor productivity measures (environmental adjusted productivity) measures respectively. The environmental damage variables are the potential environmental nitrate production (N), potential environmental pesticide impact (P) and potential nitrate-pesticide damage (N P).

Table 4. Annual Average Productivity Change of Tornqvist-Theil and Graph Malmquist Indexes of Traditional and Environmental Adjusted Productivity Measures for Potential Nitrate and Pesticide Contamination

Time Periods	**TFP**	**Nitrate EAP_N**	**Pesticide EAP_P**	**EAP_NP**
	Annual Average Growth Rate for Tornqvist-Theil Index			
1936-50	1.665	-1.200	1.665	1.957
1951-60	2.036	-1.603	2.034	1.557
1961-70	1.118	3.634	1.117	1.218
1971-80	-0.762	2.466	-0.762	-0.128
1981-90	1.506	2.389	1.508	0.341
1991-97	0.250	3.457	0.252	-0.106
1936-97	1.168	1.102	1.168	0.743
1936-80	0.812	0.211	0.812	0.919
1980-97	1.998	3.303	2.000	0.263
	Annual Average Growth Rate for Graph Malmquist Index			
1936-50	1.768	1.361	1.864	1.424
1951-60	1.550	1.250	0.575	0.197
1961-70	0.279	0.053	-1.252	-1.268
1971-80	0.054	-0.806	-0.938	-0.847
1981-90	0.141	0.710	-0.185	-0.092
1991-97	2.763	9.444	3.887	0.000
1936-97	0.897	0.860	0.311	-0.117
1936-80	0.833	0.384	-0.064	-0.139
1980-97	1.006	2.013	1.236	-0.055

Where average annual growth rate is computed as: $[(X_{t+1}/X_t)^{1/T} - 1]*100$ where X is input or output variable and T is the total time period.

Footnotes

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[1] Treatment of the externality as an output or an input will not necessarily be equivalent if total revenue does not equal total costs, because the share of the externality might then differ depending on where it is placed.

[2] There are many variations on this theme, such as the analogous proportional reduction in inputs required in time T versus time t, or the geometric average of the proportional increase in output in time T relative to that achievable in t, divided by the proportional fraction of output in time t of what could have been achieved in time t.