Sources of Productivity Growth During the Transition to Alternative Cropping Systems

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Traditional measures of productivity growth may not fully account for all sources of growth during the transition from conventional to alternative cropping systems. This paper treats soil quality as part of the production process and incorporates it directly into rotational measures of productivity growth. An application to data from an experimental cropping system in Pennsylvania suggests that both experimental learning and soil-quality improvements were important sources of growth during the system's transition.

Concern over the environmental consequences of conventional agricultural practices has led researchers to develop alternative practices and cropping systems that are designed to be both profitable and environmentally benign. Economic comparisons of alternative and conventional systems generally show that alternative practices can be competitive if there is a substantial input-cost savings, an output price premium, a reduction in revenue risk through output diversification, or an accounting of the social costs associated with agricultural pollution (Hanson et al.; Hanson, Lichtenberg, and Peters; Lee; Smolik, Dobbs, and Rickerl; Faeth et al.; Sahs and Lesoing; Ikerd, Monson, and Van Dyke; National Research Council 1989).

Data from on-farm research suggest that the soil-plant environment undergoes a biological transition upon conversion from conventional to alternative practices. Several analysts and practitioners have identified transitional costs associated with the conversion period (Dabbert and Madden; MacRae et al.; Bender) and other researchers have suggested that economic comparisons may favor conventional practices over alternative practices during this period (Hanson et al.; Andrews et al.; Culik; Janke et al.). Not always mentioned in these studies is the growth in managerial expertise and knowledge that may be required to successfully survive the transition period. Both types of transitional costs—*i.e.*, the investment in both human capital and soil capital—may present barriers to the general adoption of alternative agricultural practices (Batie and Swinton; Lockeretz).

Traditional measures of productivity growth may not completely account for all sources of growth during the transition period. In particular, productivity measures may not reflect the investment in soil quality. For example, just as Griliches and later Jorgenson and Griliches showed that observed aggregate total-factor productivity growth could be mistaken labor- and capital-quality improvements, productivity growth in an alternative cropping system could be mistaken for soil-quality improvements. Accounting for soil-quality changes may be particularly important when investigating alternative cropping practices, which are designed to increase soil quality through diverse crop rotations and green manures. Excluding this component from productivity calculations during the transition period may entangle growth due to learning with growth due to soil-quality improvements.[1] The implication is that successful economic implementation of alternative cropping systems may require both soil-quality improvements and learning by doing.

This paper treats soil quality as part of the pro-

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[1] To see the consequences from ignoring soil-quality changes in similar settings, one could turn to (i) soil productivity studies that investigate the affect erosion has on crop productivity (Crosson; Pierce et al.; Putnam, Williams, and Sawyer; Walker and Young; Xu and Prato) or (ii) recent developing country studies that have attempted to explain the observed inverse relationship between farm size and farm productivity by presenting evidence that smaller farms have higher land quality (Bhalla; Bhalla and Roy; Benjamin; Sampath).

duction process and incorporates it directly into a Malmquist-type productivity index (see Caves, Christensen, and Diewert; Färe et al.; Färe, Grosskopf, and Lovell). For example, when Färe, Grosskopf, and Roos compute productivity growth in Swedish pharmacies, they simply incorporate service-quality indicators (such as customer waiting time, promptness of service, and hours of operation) into the Malmquist index as separate outputs. When no service-quality outputs are included in their Malmquist index, productivity measurements from one year to the next show a 2.4% improvement. When service-quality outputs are included, however, the productivity increase drops to 1.8% due to a slight deterioration, on average, of same-day service and average waiting time.

The same type of direct adjustment is used here to incorporate soil quality into Malmquist productivity indexes. This adjustment requires soil-test data matched to production data, a rare combination. Fortunately data from farming-system experiments conducted at the Rodale Institute Research Center (Rodale) in Kutztown, Pennsylvania, provide a unique opportunity to construct soil-quality-adjusted Malmquist indexes of on-farm productivity. This opportunity is not without limitations and several characteristics of the data will complicate the construction and interpretation of the Malmquist indexes.

First, total organic matter is the only soil parameter that Rodale has consistently measured at the plot level and, hence, it must serve as the sole indicator of soil quality. While current research suggests that soil quality is best characterized by a broad array of soil parameters—a so-called minimum data set for soil quality (Kennedy and Papendick; Doran and Parkin; Larson and Pierce; Karlen and Stott), several studies suggest that total organic matter is one of the most important single indicators of soil quality (National Research Council 1993; Arshad and Coen; Romig et al.).

Second, it is important for productivity measures and the underlying representation of the production technology to reflect Rodale's rotational cropping systems. One method for modeling rotational production is to treat each sequential crop rotation as a single multi-year process that includes all the inputs and outputs over the entire multi-year rotation. This method, however, can lead to degrees-of-freedom problems for estimating econometric models of rotational production. One solution to this empirical problem is the use of data envelopment analysis (DEA) methods to construct a nonparametric model of the multi-year production process using mathematical programming techniques.[2] Strengths of DEA methods include: (i) the ability to estimate models using data with insufficient degrees of freedom for traditional econometric techniques such as ordinary least squares or maximum likelihood estimation, (ii) the ability to overcome extreme invariability in the data, (iii) the ability to calculate productivity measures based only on quantity data, (iv) the ability to model production without imposing a functional form, and (v) the ability to accommodate inefficiency. One weakness of DEA is a susceptibility to data outliers (Burgess and Wilson); another is a dimensionality problem where a large number of inputs and outputs relative to the number of observations can lead most or even all plots to lie on the production frontier (Leibenstein and Maital; Tauer and Hanchar). A third weakness is the general perception that there can be no statistical inference because of the deterministic nature of DEA methods (Grosskopf). Rotational crop data may lead to a dimensionality problem because of the potentially large number of crop inputs and outputs throughout a rotation. Moreover, weather data may pose a particular problem for DEA methods because abnormal, stochastic weather events can lead to data outliers. Fortunately, recent work by Banker (1996 and 1993) has explored the statistical properties of DEA estimators and can be used to test statistical hypotheses.

Third, Rodale has incorporated technological improvements into its cropping systems, particularly in its alternative (organic) systems. This practice is common to most long-term field experiments to keep cropping systems relevant (Steiner; Frye and Thomas). Because Rodale's alternative system was not well established, however, experimental learning may be the biggest source for technological improvements. For example, after evaluating early outcomes from its alternative system, Rodale switched from a short-season corn variety to the same long-season variety used in its conventional system. The Malmquist index results, however, will not distinguish experimental learning and the improvements it has generated as separate sources of growth.

Fourth, Rodale has staggered the rotation's entry point on separate fields so experimental learning potentially may be applied across fields as well as across rotations. The production model to follow does not distinguish between these two applications of experimental learning, but their implica-

[2] Lovell provides a good introduction to productivity measurement using DEA methods.

tions will be discussed along with the Malmquist index results.

And fifth, the Rodale data, like data from other experimental trials, may differ from data generated from "real-world" farming situations. However, because Rodale's systems were managed for performance and altered to incorporate new technologies—both learned and acquired, they should more closely reflect the practices of real-world farmers than more rigid agronomic trials.

With these five limitations in mind, the objectives of this paper are to develop a method for investigating the sources of growth in an alternative cropping system and apply it to Rodale's experimental data to draw inferences about the sources of productivity growth. Particular emphasis is given to the transition period, interpreted here as ending around the alternative system's fifth year. Specifically, this paper attempts to: (i) present and apply a rotational model of crop production, (ii) use DEA techniques to calculate two sets of farm-level productivity measures for Rodale, one that is adjusted to reflect soil-quality changes brought on by cropping-practice choice and one that ignores soil-quality changes, (iii) test the importance of including soil quality in the model using the hypothesis tests developed by Banker (1993 and 1996), and (iv) compare the adjusted and unadjusted measures to examine the sources of growth in Rodale's alternative cropping system.

A Model of Rotational Production and Productivity Change

The model presented here, which takes theoretical and empirical research by Chambers and Lichtenberg as a starting point, differs from traditional production models in two important ways: First, it assumes that production occurs on a rotational basis so that the technology set includes all time-dated inputs and outputs over the entire crop rotation. Second, it treats soil quality as a capital good and includes it in the technology set. Without these two important deviations from traditional models, one would be unable to attribute productivity growth to soil-quality improvements or the experimental learning that occurs after each completed crop rotation.

Following Chambers and Lichtenberg, define a crop rotation as a recurring multiyear cropping cycle, during which a sequence of crops is produced with a sequence of inputs. Let T be the number of years in a complete crop rotation. Let M and N be the maximum number of outputs and inputs for any year within a complete rotation. Let $\mathbf{y}_t \in \Re_+^M$, $t = 1, \ldots, T$, be the vector of all crop outputs produced in year t of the T-year rotation and let $\mathbf{Y} = [\mathbf{y}_1, \mathbf{y}_2, \ldots, \mathbf{y}_T]$ be the vector of all time-dated outputs produced over the entire rotation. Similarly, let $\mathbf{x}_t \in \Re_+^N$, $t = 1, \ldots, T$, be the vector of all crop inputs applied in year t of a T-year rotation and let $\mathbf{X} = [\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_T]$ be the vector of all time-dated inputs applied over the entire rotation.

Suppose that soil quality is measured at the end of the year (or growing season) and that the end-of-year soil-quality indicators in one year are equivalent to the beginning-of-year indicators in the next year. Let Q equal the number of soil-quality indicators measured during each period and $\mathbf{s}_t \in \Re_+^Q$, $t = 0, \ldots, T$, represent the vector of all end-of-year soil-quality indicators in year t. Then let $\mathbf{S}_{-T} = [\mathbf{s}_0, \ldots, \mathbf{s}_{T-1}]$ represent the vector of all the beginning-of-year indicators over the entire T-year rotation, and let $\mathbf{S}_{-0} = [\mathbf{s}_1, \ldots, \mathbf{s}_T]$ represent the vector of all the end-of-year indicators over the entire rotation.

Because productivity change may occur from one completed rotation to the next, it is necessary to date a particular rotation and the underlying inputs, outputs, and soil-quality indicators. Therefore, assume one can observe R temporally-sequenced, T-year rotations and can index each by $r \in [1, \ldots, R]$. The index, r, dates each complete rotation. It will sometimes be useful to index outputs, inputs, and soil-quality variables by the rotation number. For example, in rotation r, $Y^r = [\mathbf{y}^r_1, \mathbf{y}^r_2, \ldots, \mathbf{y}^r_T]$, $\mathbf{X}^r = [\mathbf{x}^r_1, \mathbf{x}^r_2, \ldots, \mathbf{x}^r_T]$, $\mathbf{S}_{-T}{}^r = [\mathbf{s}^r_0, \ldots, \mathbf{s}^r_{T-1}]$, and $\mathbf{S}_{-0}{}^r = [\mathbf{s}^r_1, \ldots, \mathbf{s}^r_T]$. Consider a three-crop, three-year rotation where oats, corn, and soybeans are produced in years one, two, and three. In this rotation, the vector $Y = [\text{oats}_1, \text{corn}_2, \text{soybeans}_3]$ reflects the quantity of output produced in each year of the rotation. (Conceivably, double cropping or intercropping could lead to more than one crop output in each year.) Each repeated rotation is indexed by the superscript r: so $\mathbf{Y}^1$ describes the oats/corn/soybean output for years one to three; $\mathbf{Y}^2$ describes the output for years four to six.

For rotation number r, assume the process that transforms all crop inputs and beginning-of-season soil-quality indicators throughout the rotation into crop outputs and end-of-season soil-quality indicators can be modeled by the rotational output set $\mathrm{Y}^r{}_S(\mathbf{X}, \mathbf{S}_{-T})$, where

$$\mathrm{Y}^r{}_S(\mathbf{X}, \mathbf{S}_{-T}) = \{(\mathbf{Y}, \mathbf{S}_{-0}) \colon (\mathbf{X}, \mathbf{S}_{-T}) \text{ can produce } (\mathbf{Y}, \mathbf{S}_{-0}) \text{ at rotation r}\}.$$

$\mathrm{Y}^r{}_S(\mathbf{X}, \mathbf{S}_{-T})$ allows inputs in year t to affect crop production directly in subsequent years. It treats all outputs over the entire cycle as joint outputs, thereby implicitly capturing all the biological, chemical, and physical soil processes throughout the rotation. To be useful in modeling production, output sets like $Y^r{}_S(\mathbf{X}, \mathbf{S}_{-T})$ are assumed to satisfy a number of axiomatic properties such as convexity, disposability, closedness, and boundedness.[3]

The rotational output set can be approximated for empirical purposes by constructing a reference technology, equivalent to the free-disposal, convex hull of the data, using mathematical programming techniques common to DEA (see Färe, Grosskopf, and Lovell). Let K denote the number of observations in each completed rotation and define the set of data as

$$T(K,R) = \{(\mathbf{Y}^{r,k}, \mathbf{S}^{r,k}{}_{-0}, \mathbf{X}^{r,k}, \mathbf{S}^{r,k}{}_{-T}): k = 1, \ldots, K;\ r = 1, \ldots, R\}.$$

For each rotation r, let the set of indexes be denoted as

$$I(K,r) = \{1^r, \ldots, K^r\}.$$

The approximation to the general output set, labeled as $\underline{Y}^r{}_S(\mathbf{X}, \mathbf{S}_{-T})$, is constructed according to Färe, Grosskopf, and Lovell's general method, where

(1)

$$\underline{Y}^r_S(\mathbf{X}^r, \mathbf{S}^r_{-T}) = \{(\mathbf{Y}^r, \mathbf{S}^r_{-0}): \mathbf{Y}^r \leq \sum_{k\in I(K,r)} \mathbf{Y}^{r,k} z^{r,k}, \quad \text{(i)}$$

$$\mathbf{S}^r_{-0} \leq \sum_{k\in I(K,r)} \mathbf{S}^{r,k}_{-0} z^{r,k}, \quad \text{(ii)}$$

$$\mathbf{X}^r \geq \sum_{k\in I(K,r)} \mathbf{X}^{r,k} z^{r,k}, \quad \text{(iii)}$$

$$\mathbf{S}^r_{-T} \geq \sum_{k\in I(K,r)} \mathbf{S}^{r,k}_{-T} z^{r,k}, \quad \text{(iv)}$$

$$z^{r,k} \in \Re_+, \quad \text{(v)}$$

$$\sum_{k\in I(K,r)} z^{r,k} \leq 1\}. \quad \text{(vi)}$$

The variable $z^{r,k}$, indexed by r and k, is an intensity variable indicating the role each k^{th} production observation plays in determining the frontier within rotation r. In essence, the vector $\mathbf{z}^r$ allows for convex combinations of the data. The constraints (1.i) through (1.vi) require the reference technology $\underline{Y}^r{}_{R,S}(X, S_{-T})$ to be the piecewise linear, convex hull of the data that exhibits non-increasing returns to scale and free disposability of inputs and outputs. Specifically, constraints (1.i) and (1.ii) impose free disposability on all crop outputs and soil-quality outputs throughout the entire rotation.[4] Constraints (1.iii) and (1.iv) impose free disposability on all crop inputs and soil-quality inputs throughout the entire rotation. Finally, constraint (1.vi), together with constraint (1.v), imposes non-increasing returns to scale, which allows all radial contractions of the observed data, but not radial expansions, to belong to the reference technology.[5] For the case of a single crop output and a single soil-quality output, the reference technology may be depicted as all points on or inside 0ABCD in figure 1.

The reference technology is next used to estimate a distance function (Shephard), a generalization of production function that represents the largest feasible radial expansion of crop outputs and soil-quality outputs. For the reference technology specified in (1), define the rotational output distance function as

(2)

$$D^r{}_S(\mathbf{Y}, \mathbf{S}_{-0}, \mathbf{X}, \mathbf{S}_{-T}) = [\max \{\theta > 0: (\theta\mathbf{Y}, \theta\mathbf{S}_{-0}) \in \underline{Y}^r{}_S(\mathbf{X}, \mathbf{S}_{-T})\}]^{-1}.$$

For a point like E in figure 1, the value of the distance function is given by 0E/0B. All points like E that are elements of $\underline{Y}^r{}_S(\mathbf{X}, \mathbf{S}_{-T})$ have a distance function value of less than or equal to one; all points that are not elements, like F, have a distance function value greater than one.

The rotational model allows for a well-known synergistic rotation effect, where yields from crops grown in rotations are higher than yields from crops grown in isolated monocultures (Cook; Magdoff; Power; National Research Council 1989). The rotational model accounts for this effect directly by allowing for complementary joint production throughout the entire rotation and indirectly by allowing soil-quality investment to return higher yields in later periods.

A reference technology that excludes soil quality can be derived from the reference technology in

[3] Färe and Chambers each discuss axiomatic properties of general output sets. The production technology could also be modeled with an input set or a feasible-production set. Chambers and Lichtenberg present other variations of the rotational production model that assume production within the rotation can be separated in annual production processes.

[4] Chambers and Lichtenberg suggest that free output disposability may rule out some forms of complementarity among outputs that could be essential in modeling some cropping systems. Free output disposability, however, is imposed here to rule out programming infeasibilities.

[5] The non-increasing returns constraint (1.vi), which proves useful in ruling out programming infeasibilities, is a natural consequence if at least one element of X is constant across all K observations. In the application that follows, land area (or in this case plot size) is identical for all K, a fact that transforms constraint (1.iii) into constraint (1.vi).

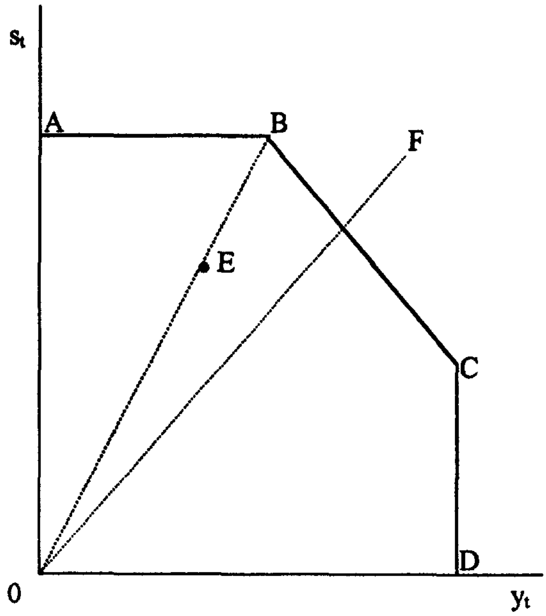


Figure 1. The Reference Technology and Distance Function

(1). Let the approximation to the rotational output set that excludes soil quality be given by

(3)
$$\underline{Y}^r_{-S}(\mathbf{X}^r) = \{\mathbf{Y}^r\text{: (1.i), (1.iii), (1.v), and (1.vi) hold}\}.$$

The set $\underline{Y}^r_{-S}(X)$ says all outputs throughout the entire rotation are produced jointly in the same production process. While it ignores contributions from soil quality, this set still accounts for a rotation effect because it, like $\underline{Y}^r_S(\mathbf{X}, \mathbf{S}_{-T})$, allows for complementary production.

As before, the approximation can be used to estimate distance functions. Define the rotational output distance function without soil quality as

(4)
$$D^r_{-S}(\mathbf{Y}, \mathbf{X}) = [\max\{\theta > 0\text{: } (\theta\mathbf{Y}) \in \mathbf{Y}^r_{-S}(X)\}]^{-1}.$$

Following Färe, Grosskopf, and Lovell's method, define the rotational Malmquist output indexes—with and without soil quality—of rotational productivity change as[6]

[6] The Malmquist index is directly related to other indexes of productivity change. Caves, Christensen, and Diewert show that if the technology of two firms can be represented by translog distance functions (with identical second-order coefficients), then the geometric mean of their Malmquist indexes evaluated for the two profit-maximizing firms under constant returns to scale is identical to the Törnqvist index of productivity change, an exact and superlative index measure.

$$(5)\ M_S(r,r+1) = \left[\frac{D_S^{r+1}(\mathbf{Y}^{r+1}, \mathbf{S}^{r+1}_{-0}; \mathbf{X}^{r+1}, \mathbf{S}^{r+1}_{-T})}{D^r_{\mathbf{S}}(\mathbf{Y}^r, \mathbf{S}^r_{-0}; \mathbf{X}^r, \mathbf{S}^r_{-T})}\right] \left[\frac{D^r_S(\mathbf{Y}^r, \mathbf{S}^r_{-0}; \mathbf{X}^r, \mathbf{S}^r_{-T})}{D_S^{r+1}(\mathbf{Y}^r, \mathbf{S}^r_{-0}; \mathbf{X}^r, \mathbf{S}^r_{-T})} \frac{D^r_S(\mathbf{Y}^{r+1}, \mathbf{S}^{r+1}_{-0}; \mathbf{X}^{r+1}, \mathbf{S}^{r+1}_{-T})}{D_S^{r+1}(\mathbf{Y}^{r+1}, \mathbf{S}^{r+1}_{-0}; \mathbf{X}^{r+1}, \mathbf{S}^{r+1}_{-T})}\right],$$

and

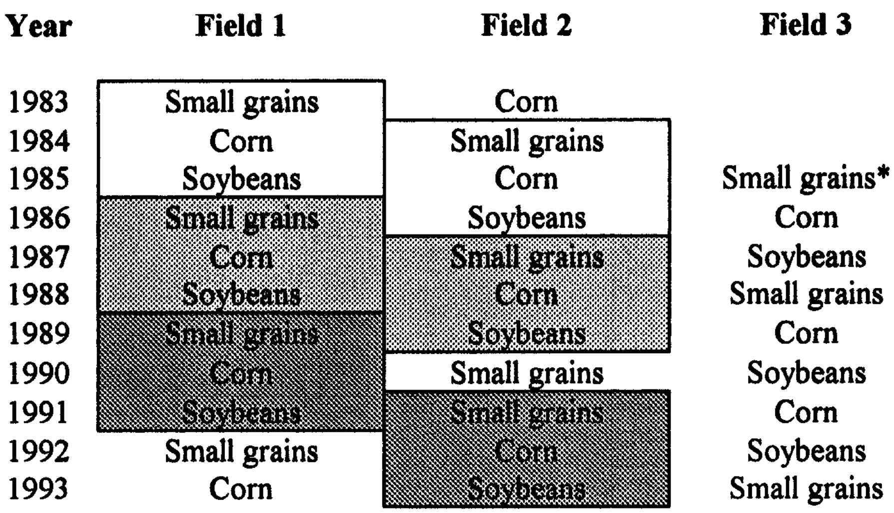
(6)
$$M_{-S}(r,r+1) = \left[\frac{D_{-S}^{r+1}(\mathbf{Y}^{r+1}; \mathbf{X}^{r+1})}{D^r_{-S}(\mathbf{Y}^r; \mathbf{X}^r)}\right] \left[\frac{D^r_{-S}(\mathbf{Y}^r; \mathbf{X}^r)}{D_{-S}^{r+1}(\mathbf{Y}^r; \mathbf{X}^r)} \frac{D^r_{-S}(\mathbf{Y}^{r+1}; \mathbf{X}^{r+1})}{D_{-S}^{r+1}(\mathbf{Y}^{r+1}; \mathbf{X}^{r+1})}\right]^{1/2}.$$

Productivity is progressive from one rotation to another if (5) and (6) are greater than one, and regressive if they are less than one. Färe et al. show that the first bracketed term in (5) and (6) is an efficiency-change index and the second term is a technical-change index.

Comparisons between (5) and (6) will address the role soil quality plays in productivity growth. In particular, Banker (1996 and 1993) suggests three hypothesis tests that can be used to determine whether two technologies are statistically different.[7] In essence, there are two separate questions to ask of the two technologies, namely (i) are the reference technologies specified by (2) and (4) statistically different, and (ii) are the productivity-, technical-, and efficiency-change index measures specified in (5) and (6) themselves statistically different. Banker's tests can be applied, in some fashion, to answer both questions.

Banker's (1996) first two tests are based on the assumptions that the reciprocals of the distance function values (often called Farrell efficiency measures) follow the exponential or half-normal distribution. Banker's (1996) third test, a Kolmogorov-Smirnov test, is useful when no particular assumptions can be maintained about the probability distribution of distance function values. The distribution-free test, therefore, is especially useful for directly comparing the Malmquist index results. Because each index calculation in (5) and (6) is a function of four distance functions, two standard distance functions and two intertemporal distance functions, it would be awkward to assume that the

[7] Grosskopf discusses recent research by S.A.C. Kittelsen that provides evidence of the small-sample properties of Banker's tests.



*** Soil organic matter measurements are unavailable for this year.**

Figure 2. Rodale's Alternative Cropping System Outputs by Year

results follow the exponential, half-normal, or any other particular distribution.

Rodale's Experiments and Data

In 1981, Rodale initiated its Farming Systems Trials, a long-term study to examine the process of converting from a conventional to an alternative cropping system. Because the goal of Farming System Trials was to compare two or more systems, variation within each system was kept to a minimum. Rodale kept input application rates for field labor and seed, among other inputs, relatively constant; however, it has tinkered with its alternative system to improve performance. Productivity measurements will pick up this tinkering as improvements in technology or efficiency due to experimental learning. Two potential sources of variation reflected in the data are year-to-year differences in weather, and plot-to-plot differences in the soil.

Malmquist indexes are calculated for Rodale's alternative system, which is based on a diverse crop rotation that relies on a green manure and mechanical cultivation for the system's fertility and pest control. The alternative system is a three-year rotation that produces a crop of small grains like oats or barley in the first year, a legume cover crop (like red clover) followed by corn in the second year, and a spring barley crop, if possible, followed by soybeans in the third year. The alternative system was started at three different points in the rotation and replicated eight times in a split-plot, randomized complete block design (Janke et al.). Each of the replications was grown on 20 by 300 foot plots. The rotation was designed as a recurring cycle so that, in the empirical analysis, its starting point can be treated as arbitrary and picked to maximize the number of usable data observations.

Figure 2 summarizes the field replications for the alternative system. Data from the replications are considered usable if rotational inputs and outputs are comparable from one rotation to the next. The figure indicates that Rodale has tinkered with the alternative system, interrupting the three-year rotation in several places. It also indicates that, in one year, soil-quality data are unavailable for one of the fields. Hence, there are only 16 usable observations (two fields times eight replicated plots) over three complete rotations for the alternative system. The clear boxes in figure 2 correspond to data observations in the first ($r = 1$) rotation; the light shaded boxes and the dark shaded boxes correspond to observations in the second ($r = 2$) and third ($r = 3$) rotations.

The reference technologies presented above require three types of data—crop yields, levels or rates of cropping inputs (including weather inputs), and soil-quality measurements—that correspond to the **Y**, **X**, and **S** vectors. Plot-level crop yields that comprise the Y vector were measured after harvesting the entire plot, excluding output from the plot borders (about 33% of the plot area), and reported on a per-hectare basis. The actual elements of Y are listed in figure 2 and in table 1. Inputs to the alternative system (elements of **X**) included yearly labor, yearly rainfall, and the nitrogen equivalent found in the green manure that precedes corn. The sole soil-quality indicators (elements of **S**) available were yearly measures of soil organic matter. Table 1 presents the mean values for all elements of the **Y**, **X**, and **S** vectors for both cropping systems. (A detailed description of the rotational data can be found in Hanson, Lichtenberg, and Peters, or Chambers and Lichtenberg.) In general, corn yields in the alternative system were lower than conventional corn yields at the start, but increased to near comparable levels by the end of the period. Soybean yields in the alternative system suffered towards the end of the period, possibly due to increased weed pressure. Soil organic matter increased substantially throughout the period. For the most part, average rainfall decreased in most years from one rotation to the next. The nitrogen equivalent of the alternative system's green manure varied widely from year to year: on average, it dropped from nearly 130 pounds per acre in the first rotation cycle to 76 and 95 pounds per acre, respectively, in the second and third cycles.

Table 1. Average Values for Rotational Outputs, Inputs, and Soil-Quality Measures for Rodale's Alternative System

	$r = 1$	$r = 2$	$r = 3$
Y			
Small grain_1	2532.4	2711.1	3580.3
Corn_2	8240.1	7938.3	9005.8
Soybeans_3	4160.2	2560.3	3051.2
X			
Labor_1	2.14	1.47	1.90
Precip_1	52.3	46.1	42.8
Labor_2	2.19	1.69	2.11
N_2	129.5	76.0	95.0
Precip_2	47.3	42.5	42.5
Labor_3	1.97	1.51	1.83
Precip_3	46.0	45.4	46.6
S			
Org. Matter_0	1.82	2.42	2.89
Org. Matter_1	2.26	2.63	2.71
Org. Matter_2	2.32	2.32	3.79
Org. Matter_3	2.42	2.66	3.51

Units:
Yields = kg/ha
Labor = hours/acre
Nitrogen equivalent (N = lbs/acre)
Precipitation = inches per year
Organic matter = %

Rodale's scientists generally estimate that the transition period for the alternative system ended in 1985 or 1986, approximately five years after the experiment's 1981 start date (Andrews et al.). If this is true, then productivity-growth measures that compare the first two completed rotations should reflect what happened as the alternative system came out of transition. Comparison between the second and third completed rotation should reflect a post-transition period.

Results

Table 2 presents the Malmquist productivity index and its technical-change and efficiency-change components from (5) and (6), calculated for Rodale's alternative cropping system. The table presents a side-by-side comparison of plot-level index calculations for the reference technology that accounts for soil quality along with the corresponding reference technology that excludes soil quality. Notice that table 2 contains two sets of calculations, one indexing the shift between the first and second rotations, and another indexing the shift between the second and third rotations.

Plot-level index calculations represent the change from one completed rotation to the next. For example, column 1 of table 2 shows that the productivity change for plot number 1 of the alternative system is 1.38600 for the rotational model with soil quality. In this case, one could say that the productivity increased 38.6% on this plot from the first to second rotations. At the bottom of the table are two rows of summary statistics: the geometric average and the variance of the sample plots. For example, table 2 shows that productivity increased, on average, 14.94% when soil quality is included in the alternative system's model.

Figures 3a and 3b present graphical summaries of the average productivity-, technical-, and efficiency-change results for Rodale's alternative system. For example, figure 3a shows that productivity increased, on average, 14.9% from the first to second alternative rotation when soil quality was included. However, figure 3b shows that this calculation dropped to 0.9% when measured from the second to the third rotation.

Table 3a presents the results of Banker's three tests. Here, the null hypothesis is that within each completed rotation the distance-function values (actually, the Farrell efficiency measures) have the

Table 2. Technical and Efficiency Change On Rodale's Alternative System Using Rotational Models that Account for Soil Quality (S) or Exclude Soil Quality (–S)

(a) First to Second Rotation

	Productivity Change		Technical Change		Efficiency Change	
Plot No.	S	–S	S	–S	S	–S
	(1)	(2)	(3)	(4)	(5)	(6)
1	1.38600	1.52411	1.38600	1.86805	1.00000	0.81588
2	1.54951	1.70780	1.54951	1.82437	1.00000	0.93610
3	1.28768	1.68184	1.28768	1.69821	1.00000	0.99036
4	1.29546	1.67372	1.29546	1.65022	1.00000	1.01424
5	1.60314	1.69577	1.60314	1.69577	1.00000	1.00000
6	1.27604	1.48813	1.27604	1.59936	1.00000	0.93045
7	1.26126	1.47285	1.26126	1.71045	1.00000	0.86109
8	1.48722	1.70406	1.48722	1.80760	1.00000	0.94272
9	0.89079	0.98266	0.89079	1.13576	1.00000	0.86521
10	1.05768	0.98303	1.05768	1.08553	1.00000	0.90558
11	0.95400	1.04832	0.95400	1.04832	1.00000	1.00000
12	0.99748	0.86802	0.99748	1.07231	1.00000	0.80949
13	1.14980	1.03822	1.14980	1.03822	1.00000	1.00000
14	0.80491	0.96585	0.80491	1.04133	1.00000	0.92752
15	0.84272	0.86869	0.84272	1.10092	1.00000	0.78906
16	0.96490	0.94067	0.96490	1.02441	1.00000	0.91826
Geo. Avg.	1.14936	1.24524	1.14936	1.35898	1.00000	0.91613
Var.	0.06516	0.12214	0.06516	0.12202	0.00000	0.00539

(b) Second to Third Rotation

	Productivity Change		Technical Change		Efficiency Change	
Plot No.	S	–S	S	–S	S	–S
	(1)	(2)	(3)	(4)	(5)	(6)
1	0.86867	0.77346	0.86867	0.78324	1.00000	0.81588
2	0.94623	0.80614	0.94623	0.77933	1.00000	0.93610
3	0.82934	0.81282	0.82934	0.81800	1.00000	0.99036
4	0.83480	0.79885	0.83480	0.79885	1.00000	1.01424
5	0.87812	0.80845	0.87812	0.80845	1.00000	1.00000
6	0.92693	0.85453	0.92693	0.79510	1.00000	0.93045
7	0.92658	1.02395	0.92658	0.82310	1.00000	0.86109
8	0.82808	0.76374	0.82808	0.77023	1.00000	0.94272
9	1.17820	1.25180	1.17820	1.17810	1.00000	0.86521
10	1.26955	1.35501	1.26955	1.21880	1.00000	0.90558
11	1.04587	1.05699	1.04587	1.11051	1.00000	1.00000
12	1.34341	1.54049	1.34341	1.20969	1.00000	0.80949
13	1.19043	1.24230	1.19043	1.24230	1.00000	1.00000
14	1.22571	1.35228	1.22571	1.21464	1.00000	0.92752
15	1.04893	1.54396	1.04893	1.17868	1.00000	0.78906
16	1.00633	1.23660	1.00633	1.20413	1.00000	0.91826
Geo. Avg.	1.00880	1.04221	1.00880	0.97542	1.00000	0.91613
Var.	0.02922	0.08033	0.02922	0.04306	0.00000	0.00539

same distribution, no matter whether soil quality was accounted for or excluded. Table 3a suggests that the null hypothesis can be widely rejected. Simply stated, the exponential, half-normal, and Kolmogorov-Smirnov tests all show that the two models, one with soil quality and one without it, are statistically different. These results add weight to assertions that soil quality can be isolated as a substantial source of growth in the alternative system.

Table 3b presents the results from Banker's third test on the productivity-, technical-, and efficiency-change calculations themselves. Formally, the Kolmogorov-Smirnov test is applied to the null hypothesis that the two distributions of index calculations, one with soil quality and one without, are identical. All but one of the individual tests in Table 3b show that there are significant differences between the two types of results; a productivity index result from the first to second rotation proves to be an exception.

The results in tables 2 and 3 and the summaries in figures 3a and 3b provide the basis for three broad conclusions: (1) a large portion of Rodale's alternative system's substantial growth was due to soil-quality improvements; (2) the large productiv-

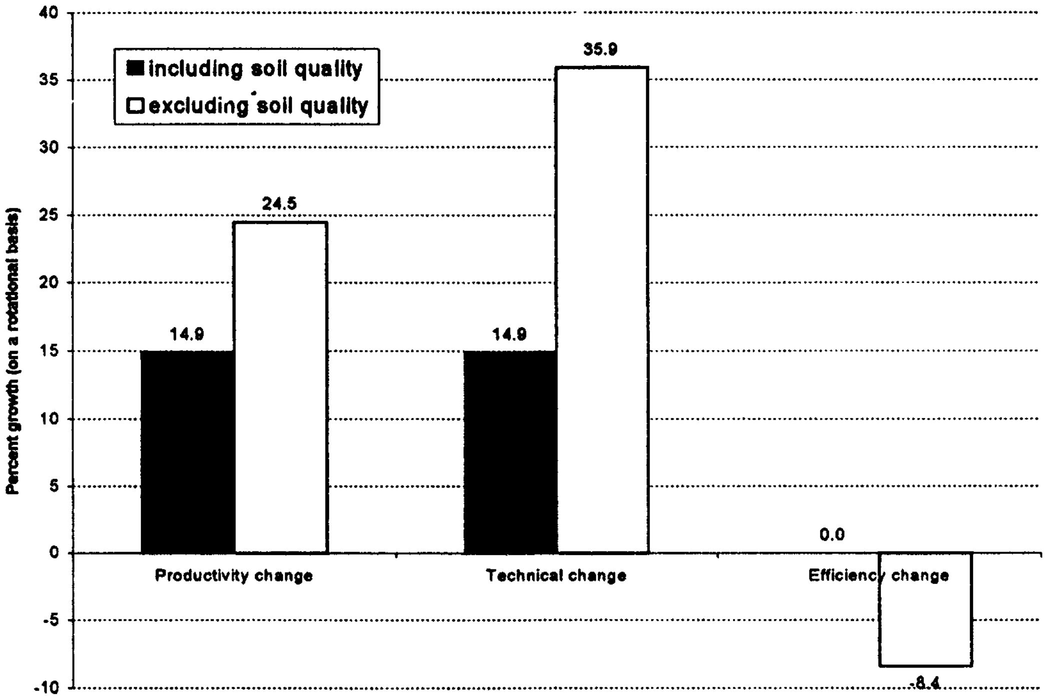


Figure 3a. Average Malmquist Index Results for Rodale's Alternative System: First to Second Rotation

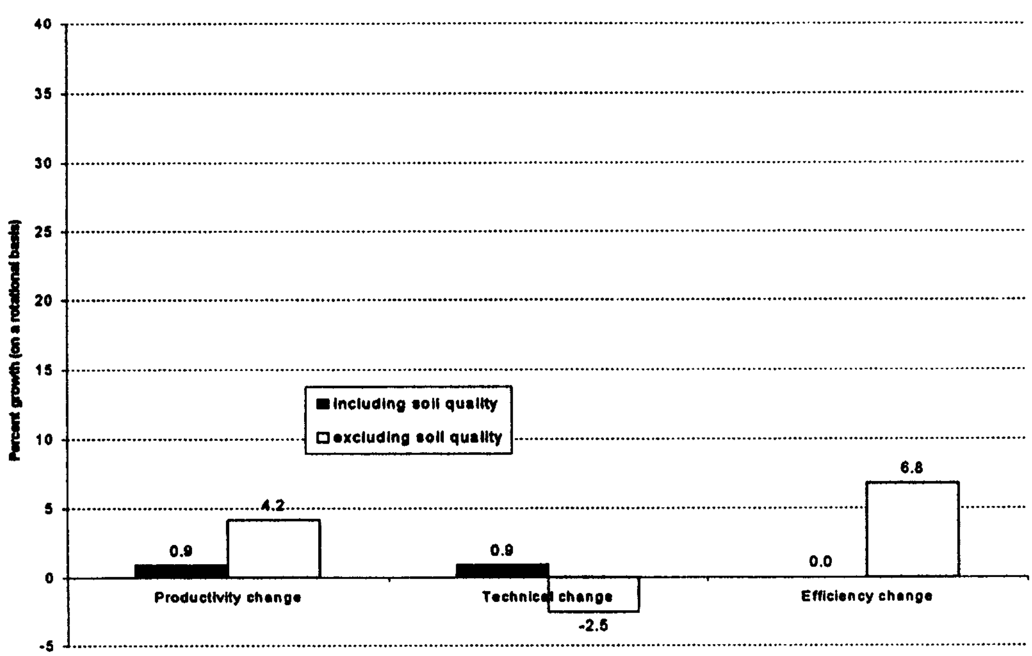


Figure 3b. Average Malmquist Index Results for Rodale's Alternative System: Second to Third Rotation

Table 3. Are the Rotational Models With and Without Soil Quality Statistically Different?*

(a) Results from Banker's three hypothesis tests based on the calculated value of the distance functions

	Exponential Test	Half-Normal Test	Komorgorov-Smirnov Test
First rotation	yes	yes	yes
Second rotation	yes	yes	yes
Third rotation	yes	yes	yes

(b) Results from Banker's nonparametric Kolmorgorov-Smirnov test based on the index calculations

	Productivity Change	Technical Change	Efficiency Change
First to second rotation	no	yes	yes
Second to third rotation	yes†	yes	yes

*One-tailed tests at the 97.5% confidence level, unless otherwise noted.
†Significantly different using a one-tailed test at the 95% confidence level.

ity-growth residual that remained after soil quality is accounted for can be attributed to experimental learning; and (3) these two sources of growth, learning and soil-quality improvements, were especially important as the alternative system emerged from the transition period.

Soil-quality improvements

The Malmquist index calculations, on average, show that soil quality was an important source of the alternative system's overall growth because, when soil quality was unaccounted for, productivity growth and technical change were substantially overestimated. For example, figures 3a and 3b show that average productivity growth is overestimated by 9.6% (24.5% versus 14.9%) from the first to second rotation and by 3.3% (4.2% versus 0.9%) from the second to the third rotation. The figures show the same pattern for technical change, although the technical-change measurement from the second to the third alternative rotation provides an exception to this pattern. To the extent that quality improvements explain a large portion of productivity growth and technical change, these results are reminiscent of Jorgenson and Griliches's results. Here the results suggest that soil quality explains a large part of the supposedly unexplained productivity-growth and technical-change residual observed in Rodale's alternative system, especially during the first two completed rotations.

Productivity results for some individual plots contradict the average results. For example, table 2 shows productivity growth from the first to second rotation is underestimated on four individual plots when soil quality is omitted; and from the second to third rotation, productivity growth is underestimated on seven individual plots when soil quality is omitted. This apparent contradiction (with individual results contradicting the average results) provides a lesson on interpreting the results. When examining productivity growth, one considers relative, not absolute, growth in inputs and outputs. Because the rotational model treats soil quality as both an input and an output, a soil quality improvement has implications on both soil-quality input growth and soil-quality output growth. When growth in the soil-quality output is greater than growth in the soil-quality input, one might understate productivity growth when soil quality is omitted (even if absolute levels of soil quality are increasing). Put another way, positive levels of soil-quality growth are consistent with higher productivity growth measures after accounting for soil quality.

Experimental learning

Figures 3a and 3b (along with table 2) provide evidence that substantial learning occurred in the alternative system, even after accounting for soil quality. For example, productivity in the alternative system improved 14.9% over the first two rotations, a six-year period. Because the rotational model accounts for labor, nutrients, weather, and soil quality, these factors are unlikely to be the source of productivity growth or technical change unless the available data are misrepresentative.[8] However, information on at least one major factor is missing in the production model: managerial expertise. Experimental learning is the likely source of the managerial improvements and, therefore, the productivity-growth and technical-change residual. As mentioned above, Rodale has acted on this experimental learning by tinkering with the alterna-

[8] According to Rodale, monthly rainfall may better characterize weather differences than annual rainfall, which is used in this study. Furthermore, because a single soil parameter may inadequately reflect soil quality, soil quality may be misrepresented.

tive system. Unfortunately, experimental learning and the tinkering it has generated cannot be distinguished as separate sources of Rodale's technical progress. In this case, the high rates of technical progress may be documentation of the tinkering itself.

As mentioned in the introduction, the staggered nature of Rodale's experimental design may further complicate the issue of experimental learning. The staggering in figure 2 suggests that learning from field one could be applied to field two, resulting in higher initial performance in field two but lower initial productivity growth. Indeed the indexes for individual plots in table 2 reflect the possibility of across-field learning from the first to second rotation: plots 1–8 (field one) have higher productivity growth than plots 9–16 (field two).[9] This scenario is reversed, however, when results from the second to third rotations are examined. Hence, across-field learning, if it is occurring, is limited to the early part of the experiment. The reversal in field-to-field differences in productivity-growth results may be explained, at least in part, by the cyclic nature of productivity measures. For example, low productivity in rotation r can lead to negative productivity-growth measurements from $r - 1$ to r but positive measurements from r to $r + 1$.[10]

Transition period

If Rodale's transition period lasted five years or so, then the productivity results that compare the first two alternative rotations roughly demonstrate what happened when the system emerged from the transition period. Figures 3a and 3b show that productivity and technical change improved substantially from the first to the second rotation but only slightly from the second to the third. These observations are just what one would expect when the emergence occurs during the first measurement period but not the second.

Conclusion

Results show that the rotation-based productivity measures that ignore soil quality, on average, overstate productivity growth for Rodale's alternative cropping system, which features a nitrogen-rich green manure. Results also show that the alternative system's high initial rates of productivity growth drop after two complete rotations. Taken together, these results suggest that the high growth rate observed as Rodale's alternative system emerged from the transition period can be directly attributed to two sources: returns on soil capital investment and/or gains from experimental learning.

These results are in several ways intuitive or anticipated. For example, it makes sense that productivity growth was overstated when soil quality was excluded because the alternative system was designed to achieve high crop yields by building up soil capital. If the investment in soil quality was unaccounted for, the growth in yields as the system emerged from transition would appear to be unexplained and therefore may have been assigned to technical progress. By comparing productivity measures with and without soil quality, one clearly sees that the investment in soil quality was a major source of growth.

It is also intuitive that the technical progress, or learning, associated with Rodale's alternative system would grow at a high pace, especially as the alternative system emerged from the transition period. At the start of the experiment, Rodale's alternative rotation was new, untested, and unsupported by a fully developed network of alternative agricultural practitioners and researchers. For example, Rodale's experiments were already at least five-years old when research on alternative agricultural practices entered federal agricultural policy (in the form of the Low-Input Sustainable Agriculture research and education program, which saw authorization in the 1985 Farm Bill and appropriations in 1988). In other words, Rodale practitioners could expect to face a steep learning curve on their alternative system. This paper's contribution is the confirmation of these expectations by documenting the sources of growth during the transition period through the application of recently proposed theoretical models and hypothesis tests.

By documenting these two sources of growth, the paper also exposes an issue underlying the critical economic question of whether alternative systems can be economically competitive with conventional systems. The productivity results, while not designed to evaluate economic competitiveness, do suggest that to be practitioners of alternative systems must overcome two transitional costs—investments in soil capital and management capital—to survive the transition period.

[9] Banker's Kolmorgorov-Smirnov test confirms that productivity results from plots 1–8 are significantly different than results from plots 9–16. (Banker's two parametric tests cannot be applied because a dimensionality problem, which causes all plots to have a distance function value equal to one, necessitates division by zero.) Thanks to an anonymous reviewer for suggesting both that across-field learning may explain the results and that Banker's test may be useful.

[10] For comparison's sake, annual productivity-growth reversals are fairly common in Ball et al.'s total factor productivity results over a similar 15-year period for the aggregate agricultural sector.

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