August 1997 **No. 413**

Recovering a Soil Quality Measure from Crop Trials Data: A Dynamic Econometric Method

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Acknowledgements

Univ. of Wisconsin-Madison, Dept. of Agricultural and Applied Economics, Staff Paper Series No 413. Financial support from a Hatch grant is gratefully acknowledged. Data used in this paper came from experiments initiated by Dr. A.E. Peterson, and were supplied by Dr. Larry G. Bundy. We are grateful to Dr. Larry G. Bundy for assistance in interpreting the data and results, and to Drs. Kevin McSweeny and Phillip Barak for comments on earlier drafts. Remaining errors are ours alone.

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Abstract

The definition and measurement of soil quality is a challenge faced by all researchers concerned with the environmental consequences of agricultural land use. Conceptual difficulties, lack of suitable data and the need for a methodology capable of capturing long-term changes are all serious constraints. In this paper we develop a new approach to measuring soil quality from longitudinal data on yields and certain farm management practices. These data are widely available from crop trials experiments. The methodological core is a dynamic model that, in its most general form, is capable of linking the evolution of soil quality, as the key state variable, to farm management practices and important observed outcomes such as yields. Implementation makes use of a non-linear time-series estimation procedure that exploits both the recursive properties of the dynamic model and the availability of longitudinal crop trials data. Estimation results shed light on the hypothesized evolution of soil quality in the short and long run under different crop rotations and fertilizer applications, and reveal some interesting dynamic relationships. As such, our measure has potential applications in the design of public policy and in the valuation of agricultural land.

Key Words: soil quality, dynamic econometric method

Introduction

In the analysis of the environmental consequences of agricultural land use, the problem of measuring soil quality is pervasive. The effects of agricultural production on land quality are felt over many years and depend on a wide range of initial conditions and land management practices. It is not clear how measures of the many physical and chemical properties of soils should be combined to provide a single measure of "soil quality" (Karlen et al. 1997). Furthermore, time series of measures of the physical and chemical properties of soils under different management regimes are very expensive to construct and scarce to obtain. In this paper we develop a new approach to measuring soil quality from longitudinal data on yields and certain farm management practices that are widely available from crop trials experiments. The conceptual core is a dynamic model that, in its most general form, is capable of linking the evolution of soil quality to farm management practices and important observed outcomes, such as yields, environmental protection, or soil health (Granastein and Bezdicek, Rodale Institute). Implementation requires a non-linear time-series estimation procedure that exploits both the recursive properties of the dynamic model and the availability of longitudinal crop trials data. The measure could have valuable private and public uses, because it provides the basis for examining the actual effects of farm management practices on soil quality evolution and valued productivity, environmental or health outcomes.

The new approach addresses three basic challenges that direct soil quality index measures have not. First, by recovering a soil quality measure indirectly, it implicitly combines all relevant soil properties rather than necessitating the selection of a few physical, biological, or chemical properties (Rhoton and Lindbo), avoiding the "heterogeneity" problem that arises when constructing indices directly from actual combinations of soil properties in different areas. Second, it provides a measure based on revealed outcomes rather than an individual soil properties (such as soil depth) or indexes of these with arbitrary weights (Karlen et al. 1994a,b). Thus, the expected effects of alternative practices can be evaluated directly by testing the sensitivity of the recovered soil quality measure to changes in the values of variables that shape it. Third, the additional costs of wide-spread implementation and refinement of this approach are low because the necessary time-series data are already available from crop trials experiments in many states.

The new approach can also be viewed as complementing existing efforts (Halvorson Smith, and Papendick (1997) and Karlen et. al (1994a,b)) by providing an aggregate benchmark against which more direct summary measures of soil quality might be evaluated. Certain mathematical restrictions are necessary to estimate the model, and these result in an ordinal—rather than a cardinal—index of soil quality. As a result, soil quality comparisons associated with different farm management practices within and across locales using this method will be limited to relative measures. Yet, as is well-known (Halvorson, Smith, and Papendick (1997)), direct index measures of soil quality have severe comparability problems because of heterogeneity in soil types, climatic zones, and other bio-physical factors. Therefore, a correct weighting scheme of any soil quality index based on direct measures of soil properties would also have to be adjusted for different environments in a way that may only allow ordinal comparisons.

The paper is structured as follows. The next section develops the general dynamic model, with a state equation depicting several factors that are likely to shape the evolution of soil quality and a flow equation in which soil quality is one input to the production of a desired outcome (in this case, corn production). Following the presentation of the general modelling approach, data from a crop trials experiment in Lancaster, Wisconsin are described and refined so as to be useful in the subsequent estimation. Next, the dynamic modelling approach is refined to enable its econometric application to the Lancaster crop trials data, and the estimation results are presented and discussed. The econometric estimates are both statistically robust and consistent with the prevailing wisdom on the effects of crop rotation and fertilizer on production and soil quality. In the penultimate section, we use these estimates to conduct a brief examination of major issues like how long-run soil quality is affected by crop rotation choices, nitrogen application, and set-aside programs, such as the Conservation Reserve Program. The conclusion summarizes the advances and limitations of the results and this new method of recovering soil quality measures from crop trials data.

A Dynamic Model of Soil Quality and Valued Outcomes

The recursive dynamic model explains outcome measures and the evolution of the soil quality state variable. Possible outcome measures include crop yield, the environmental mediation associated with a land unit, or the contribution of the land to the broader ecological web. For the remainder of this paper, however, we concentrate on yield as the variable of interest. Equation (1) is a production function, where Y_t, the yield of a crop at time t, is modelled as a function of a variety of contemporaneous factors: soil quality (Q_t), tillage practice (T_t), the level of nitrogen applied to the land (N_t), other inputs (OI_t), the weather related variables (W_t):

$$Y_t = f(Q_t, T_t, N_t, OI_t, W_t). \tag{1}$$

Equation (1) cannot be estimated alone because we lack information on Q_t. However, the evolution of soil quality can be inferred in a time series by examining the effects of previous decisions regarding land use and practices. These are captured in soil quality state equation (2):

$$Q_t = g(Q_{t-1}, CR_{t-1}, N_{t-1}, OF_{t-1}) \tag{2}$$

This equation says that soil quality at the start of period t is a function of past values of soil quality; crop rotation choices; fertilizer application levels; and other factors (OF). This specification reflects the recursive nature of the soil quality dynamics, or the fact that soil quality at a certain period cannot be determined only by choosing the values of control variables, such as crop rotation or fertilizer levels in the previous period. Estimating the state equation requires a means for recovering the parameters which govern equation (2). Substituting equation (2) into (1) gives a nested production function:

$$Y_t = f(g(Q_{t-1}, CR_{t-1}, N_{t-1}, OF_{t-1}), T_t, N_t, OI_t, W_t), \tag{3}$$

which is potentially estimable by means of successive substitution.

Estimation requires choice of functional forms for f(·) and g(·). For f(·), we use a translog production function, which expresses the logarithm of output as a generalized quadratic function of the logarithm of inputs. This functional form ensures that substitution relationships between soil quality and crop management practices, such as fertilizer application, are unrestricted. The production function f(·) then becomes:

$$\ln Y = a_0 + \sum_i b_i \ln \mathbf{X}_i + \frac{1}{2}\sum_i \sum_j b_{ij} (\ln \mathbf{X}_i)(\ln \mathbf{X}_j), \tag{4}$$

where $\mathbf{X} = [Q_t, T_t, N_t, OI_t, W_t]$ is a vector of input variables.

In the empirical estimation presented below, we assume g(·) to be a Cobb-Douglas function.[1] Although this choice imposes strong restrictions on the elasticities of substitution across factors (i.e., that they are constant and equal to unity), the log-linearity of Cobb-Douglas form ensures that the successive substitution and the estimation procedures are computationally tractable. After a logarithmic transformation and the successive substitution of Q_t, the state equation g(·) becomes:[2]

$$\ln Q_t = \sum_{j=1}^{T} \alpha^{j-1} \beta \ln \mathbf{S}_{t-j}, \tag{5}$$

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[1] The general form of a two-input Cobb-Douglas production function is

$$y = x_1^{\alpha} x_2^{\gamma},$$

where y is output, the x_i are inputs of production, and α, γ are the parameters governing returns to scale. Generally, the function is assumed to have non-increasing returns to scale (with $\alpha + \gamma \leq 1$). Note also that this production function is characterized by a constant elasticity of substitution between factors.

[2]
$$\begin{aligned} \ln Q_t &= \alpha \ln Q_{t-1} + \beta \ln \mathbf{S}_{t-1} \\ &= \alpha(\alpha \ln Q_{t-2} + \beta \ln \mathbf{S}_{t-2}) + \beta \ln \mathbf{S}_{t-1} = \alpha^2(\alpha \ln Q_{t-3} + \beta \ln \mathbf{S}_{t-3}) + \alpha \beta \ln \mathbf{S}_{t-2} + \beta \ln \mathbf{S}_{t-1} \\ &= \ldots \\ &= \alpha^T Q_{t-T} + \alpha^{T-1} \beta \ln \mathbf{S}_{t-T} + \alpha^{T-2} \beta \ln \mathbf{S}_{t-T-1} + \ldots + \alpha \beta \ln \mathbf{S}_{t-2} + \beta \ln \mathbf{S}_{t-1}. \end{aligned}$$

where **S** is the vector of soil quality input variables other than Q, β is the vector of parameters associated with those inputs, and the initial soil quality (Q_{t-T}) is normalized to zero.[3] The final step involves substituting (5) into (4) to derive a nested production function which depends only on the observed variables. This non-linear function can then be estimated to recover the parameters of interest (α and β) which govern the evolution of soil quality.

Implementing this dynamic model depends not only on specifying the functional forms that are to be substituted into the recursive dynamic model, but also on choosing the explanatory variables to be included in the two equations governing yields and soil quality. Of course, only variables whose values display variation over time can be incorporated in a time-series model. By implication, soil quality measures and yield outcomes can only be as comprehensive as the underlying experimental data, which means that the experimental design shapes which practices and outcomes can and cannot be examined from a given crop trial. In our data, for example, tillage method remained unchanged throughout the series (all plots were chisel plowed in the fall and disked in the spring), so our soil quality measure is unable to capture the effects of variations in tillage practices.

Before turning to the data we summarize the attributes of the dynamic model just presented. First, it allows the statistical recovery of a summary measure of soil quality derived from actual performance and farm management data. Performance in this case is measured as yield, although in a different experimental setting it could be measured as environmental remediation or soil health. Second, the measure is constructed primarily from longitudinal data on farm management practices and outcomes. These data are much more widely available than are series of soil chemical properties and other factors used in construction of direct soil quality measures. Third and finally, the approach allows for comparisons across regions, in terms of the proportional effects of different farm management practices on soil quality.

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[3] Otherwise, it is impossible to express soil quality as a function only of inputs in a finite time horizon setting. This normalization is readily rationalized on the grounds that the effects of initial

The Lancaster Crop Trials Data

Since 1967, the University of Wisconsin Agricultural Research Station near Lancaster, WI has been the site of a long-term study of yields of economically important crops under a legume-cereal rotation (Higgs, et al., 1976; Baldock et al., 1981). The experiment has been conducted on a well-drained Rosetta silt loam soil that is representative of the forested unglaciated soils in Major Land Resource Area 105 (Vanotti and Bundy, 1995), or of approximately 19 million hectares of the Upper Mississippi Valley, including parts of Iowa, Illinois, Minnesota, and Wisconsin. Five different crop rotations were undertaken to evaluate the nitrogen supply capability of legumes (alfalfa and soybeans) for succeeding cereal crops (corn and oats). The original rotations were continuous corn (CCCCC), corn-soybeans-corn-oats-alfalfa (CSCOM), corn-corn-corn-oats-alfalfa (CCCOM), corn-corn-oats-alfalfa-alfalfa (CCOMM), and corn-oats-alfalfa-alfalfa-alfalfa (COMMM). In 1977, the oats crop was removed from two of the rotations (CCCOM became CCCMM and COMMM was modified into CCMM and MMMMM). Again, in 1987 the 4-year rotation of CCMM was modified to study 2-year legume-cereal rotations, CM and CS. So, in total, there are seven different crop rotations which have been tested in this experiment.

In a given year, there are 21 crop sequence plots of 6.1 by 36.6 m plus replicate plots, so yielding a panel structure of 42 plots by 29 years (through 1995). This panel structure is further enrichened by the fact that the experiment also involved applying different levels of nitrogen fertilizer (ammonium Nitrate - N) to sub-plots of corn production. Between 1967 and 1976, a given corn plot had 0, 84,168, or 336 kg of N ha^{-1} applied to sub-plots, and these application levels were modified to 0, 56, 112, and 224 kg of N ha^{-1} from 1977 to the present. No other crops received any fertilizer N. When we break the data down by plot and N application accounting for

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soil quality on Q_t presumably diminish as T increases.

the fact that N levels vary within a plot only when corn is planted, we have $42\times4\times29 = 4872$ observations on crop yields.

Data on climatic conditions such as temperature and precipitation are available from 1972 to 1995, which reduces the data set used in the subsequent estimation to 24 years. The experiment controlled for other input conditions by maintaining adequate levels of P and K for all crops, applying herbicides, insecticides, and undertaking two cultivations to control corn and soybean pests (Baldock et al., 1981; Vanotti et al., 1995). As mentioned above, tillage practices remain constant throughout the series and cannot be examined. Thus, the two farm management practices that can be explicitly examined for their effect on soil quality using the Lancaster crops trial data are rotation and fertilizer levels.

Developing a Rotation Index

The Lancaster experiment focuses on how crop rotations and varied levels of N fertilizer applications influence cereal yields, especially corn. To estimate the dynamic model set forth above, we need an index to capture the effects of crop and rotation choices. The task is complicated by the high correlation between N fertilizer application and corn production built into the experimental design; as a result, it is necessary to combine information on crop rotation and N fertilizer applications into a single index.[4] In this section, we explain the construction of the rotation index. The discussion focuses on the N uptake and N carryover associated with cropping choices and N application levels. Given that the outcome equation under study is corn yields, the effective reduction of the rotation index to a measure of relative N outcomes seems reasonable.

The first step is to assess the N uptake by succeeding crops. Using the same data from 1987 to 1991, Vanotti and Bundy (1994) report N uptake by oats to be 87.4 kg ha^{-1}; for data

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[4] The alternative is to face a serious multicollinearity problem if the rotation index and N fertilizer application levels are both included as explanatory variables.

spanning 1983 to 1985 Vanotti, Leclerc, and Bundy (1995) measured the mean N uptake by the succeeding corn crop as 108.6 kg ha^{-1}. Because alfalfa and soybean add N to the soil, they can be characterized as having a negative N uptake. Vannoti and Bundy (1995) estimate the legume fertilizer replacement values based on plot yields and response functions of 3rd year corn in a CCCMM sequence as 153.4 and 35.8 kg ha^{-1} for the first and second year after alfalfa, respectively, and 75 kg ha^{-1} for the first year after soybean. For the second year after soybean, the estimated average effect of soil N availability was the equivalent of -35.8 kg ha^{-1} uptake (because part of the N contribution of soybean to first year corn is accomplished at the expense of subsequent reductions in N availability).

These N uptake measures need to be augmented to incorporate the N carryover effect associated with the application of N fertilizer on corn production. Using oat yield response data from the Lancaster experiment between 1967 and 1986, Vanotti and Bundy (1995) estimated the amounts of N fertilizer carried over from corn production. On corn plots with 84 kg ha^{-1} of N applied, carryover averaged about 21% of applied N or just over 17 kg ha^{-1}. Plots with higher N rates demonstrated a significant increase in carryover, with rates equal to 40%, 41%, and 48% of applied N, respectively, for application levels of 112, 168, and 224 kg ha^{-1}. N carryover effects after the second year of application are arguably negligible and we do not include them in our analysis. From these carryover rates we can impute N use efficiency at different levels of N applications. For N applications of 84, 112, 168, and 224 kg ha^{-1} respectively, the efficiency rates are 79, 60, 59, and 52 percent respectively.

The complete rotation index, incorporating N uptake or replacement and N carryover for corn, is shown in Figure 1 and is denoted by R_t in the remainder of this paper. For example, if corn with no N fertilizer is planted on plot i in year t-1, then the rotation index for plot i in year t takes a value of 108.6. If soybean is planted in year t-2 in a CSCOM sequence with no N fertilizer application for corn in t-1, then the values of the rotation index for years t-1 and t are -75 and 144.5 respectively. The second measure of 144.5 for year t reflects the N uptake of 108.6

from planting corn without fertilizer at t-1 plus a carryover of 35.8 from the second year after soybeans. Another noteworthy feature of Figure 1 is that it illustrates the strictly negative relation between N fertilizer application and the amount of N uptake by corn, reflecting the well-known fact that where yields are concerned, N fertilizer serves as a short-run substitute for soil quality.

Econometric Recovery of a Soil Quality Index

In this section, we present an econometric method and results for estimation of a specific form of the model developed in equations (1) - (5). As mentioned above, data constraints impose some restrictions on the fitted model. Accordingly, we estimate a production function and nested state equation of the form

$$Y_t = f(Q_t, N_t, Prec_t, G_t)\text{, and} \tag{6}$$

$$Q_t = g(Q_{t-1}, R_{t-1}), \tag{7}$$

where $Prec_t$ is July precipitation and G_t is July growing degree days. Note that in (7), the only term directly influencing the evolution of soil quality over time is the accumulated rotation index, which captures previous crop choices and N application levels. Thus in the model to be estimated, the soil quality state equation (5) becomes:

$$\ln Q_t = \sum_{j=1}^{T} \alpha^{j-1} \beta \ln R_{t-j}\,, \tag{8}$$

where R is the rotation index and β is its response parameter.

Before undertaking the estimation, it is necessary to resolve one important identification problem associated with the nested production function. That problem is revealed by considering the soil quality state equation (7) prior to the successive substitutions that produce equation (8). This equation can be written following the logarithmic transformation of the Cobb-Douglas production function as:

$$\ln Q_t = \delta Z^{\mathrm{T}}, \tag{9}$$

where $\delta = [\alpha, \beta]$ and $\mathbf{Z} = [\ln Q_{t-1}, \ln R_{t-1}]$. Substituting (9) into the translog production function (4), we can recover the estimated coefficients associated with the soil quality variables as:

$$\begin{aligned}
\varepsilon_1 \ln Q_t &= b_1 \delta \mathbf{Z}^{\mathrm{T}}, \\
\varepsilon_{11} (\ln Q_t)(\ln Q_t)^{\mathrm{T}} &= b_{11} (\delta \mathbf{Z}^{\mathrm{T}})(\mathbf{Z} \delta^{\mathrm{T}}), \\
\varepsilon_{12} (\ln Q_t)(\ln N_t) &= b_{12} (\delta \mathbf{Z}^{\mathrm{T}})(\ln N_t), \\
\varepsilon_{13} (\ln Q_t)(\ln G_t) &= b_{13} (\delta \mathbf{Z}^{\mathrm{T}})(\ln G_t), \\
\varepsilon_{14} (\ln Q_t)(\ln Prec_t) &= b_{14} (\delta \mathbf{Z}^{\mathrm{T}})(\ln Prec_t),
\end{aligned} \tag{10}$$

where ε_{ij}'s are the estimated coefficients. The identification problem arises because it is impossible to separate b_1 from δ and therefore recover the parameters of interest (α and β) from ε_1 without imposing a restriction on the value of b_1. By setting $b_1 = 1$, it is possible to solve the identification problem for the rest of the system, because ε_1 then identifies δ. This normalization changes the absolute values of the coefficients of the nested production function, but leaves their relative sizes unaffected. It is this property of the estimating model that results in an ordinal rather than a cardinal measure of soil quality.

The nested corn production function was estimated using NLS (Non-linear Least Squares) method, and the only terms added to the specification suggested above were a dozen categorical variables to control for changing seed varieties.[5] The estimation results presented in Table 1 have the expected signs, display a high level of significance, and explain a sizable proportion (56%) of the observed variation in yields.

Estimates of α and β, parameters governing the dynamic evolution of soil quality have expected signs and magnitudes. The former (α) reflects the dynamic effects of rotation on soil quality over time, and its value (0.647) indicates that the effects of rotation decrease as time elapses. The latter (β) captures the current effect of the rotation index on soil quality. Because N

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[5] The term for the square of soil quality ($(\ln Q_t)(\ln Q_t)^{\mathrm{T}}$) was dropped in estimation due to high collinearity with $\ln Q_t$.

uptake is measured positively, the estimate of $\beta = -0.058$ confirms the expectation that soil quality will decline with more intensive cultivation of corn. As expected, N fertilizer input has a positive impact on corn yield (the estimated coefficient value is 0.097) when controlling for other inputs. The quadratic term in N fertilizer (-0.005) captures the anticipated concave relationship between the level of N fertilizer and corn yields (i.e., declining marginal impact of N on yields); however, the coefficient is not statistically significant.

The interaction terms reveal an interesting relationship between soil quality and N fertilizer application levels. The coefficient of the quadratic term ((ln Q)(ln N)) is negative (-0.242) and statistically significant at 1%. This coefficient value can be interpreted in two ways: (1) the marginal effects of soil quality on yields tend to decrease as the level of N fertilizer application increases; or, (2) the marginal effects of N fertilizer decrease as soil quality increases. In other words, the marginal productivity of N fertilizer is inversely related to soil quality.

In order to illustrate the degree of this inverse relationship between marginal productivity of N fertilizer and soil quality, we can derive the marginal productivity of N fertilizer as a function of soil quality from the estimated coefficients of the nested production function:

$$\frac{\partial y}{\partial N} = \frac{Y}{N} \cdot \left(0.097 - 0.005 \ln N - 0.242 \ln Q - 0.003 \ln G + 0.001 \ln P\right), \tag{11}$$

where the values of all variables in the RHS except N and Q are held constant at their means. Figure 2 shows how soil quality variation affects the marginal productivity of N fertilizer given four different levels of current N application. The conditional variable, i.e., soil quality, is recovered using the estimation results (α and β); the relative measures of soil quality at time t for 20-year continuous corn and continuous alfalfa rotations are approximately 0.85 and 2.05 respectively. Because initial soil quality level, in this case Q_{t-20}, is unknown and we have an identification restriction ($b_1=1$), only relative values of the marginal product data are relevant. As conventional wisdom would suggest, the marginal productivity of N fertilizer given poor soil quality (as represented by a continuous corn rotation) is higher than that of good soil quality (as represented by a continuous alfalfa rotation). This simulation again confirms the inverse relationship between the marginal productivity of N fertilizer and soil quality.

More on the Dynamics of Soil Quality

The econometric estimates reported in the previous section can be used to analyze how crop rotation, N fertilizer application, and land use interventions such as the Conservation Reserve Program affect the dynamics of soil quality. In the case of crop rotation, it is widely known that soil quality should decrease (increase) if continuous corn (alfalfa) rotation is selected over several time periods. However, the dynamics of this process, i.e., how distinctive are the time-paths of soil quality under different rotations are not well understood. Figure 3 illustrates the soil quality dynamics of four different crop rotations (with four N fertilizer applications), and shows as expected that continuous corn rotation decreases soil quality by about 50% throughout the selected time horizon (10 years), while continuous alfalfa rotation increases soil quality by more than 45%. In each case, most of the soil quality measure changes occur within 5 years.[6] It is also noteworthy that in the case of the CCCMM (168) rotation, soil quality increases remarkably in years t+4 and t+5 of the sequence, demonstrating the restorative effect of alfalfa on soil quality.

The dynamic effects of N fertilizer on soil quality can be portrayed in a similar manner. Using the case of continuous corn with four levels of fertilizer application, Figure 4 shows that applying N fertilizer yields only slight improvements in the evolution of soil quality in the long run. Compared with the base case of zero fertilizer, the long-run difference in soil quality ranges from 3.5% at 56 kg N ha^{-1} to 7.5% at 224 kg N ha^{-1}. Thus, while N fertilizer can contribute significantly to maintaining yields in the short run, it does not offer much to the maintenance of

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[6] The log-linear Cobb-Douglas function characterizes a quadratic in which the slope approaches zero as the amount of the input increases. The robustness of our finding with respect to more flexible functional forms is a subject for further research.

underlying long-run soil quality relative to the benefits offered by crop rotation. This finding contradicts those of some previous studies in the economic literature on soil quality. In particular, it provides no support for the widely cited conclusion of Burt (1981) that "intensive wheat production with good cultural and *fertilizer* practices ... is not a threat to the long-run productivity of soil [italics added]". Since we focus on the soil productivity aspect of soil quality in the analysis, we now argue that N fertilizer cannot be a substitute for the long-run productivity of soil.

The soil quality index can also be manipulated to create a measure of soil quality regeneration when land is left fallow. Such a measure can be used to evaluate the soil quality impacts of programs like the U.S. Conservation Reserve Program (CRP), which aim to promote soil conservation through fallowing and related measures. To derive this measure, we return to the state equation (7) in levels:

$$Q_{t+1} = Q_t^{\alpha} R_t^{\beta} . \tag{12}$$

The regeneration rate of soil quality can then be derived by dividing both sides of (12) by Q_t to obtain:

$$r_t | (Q_t, R_t) = (\frac{Q_{t+1}}{Q_t}) = Q_t^{\alpha - 1} R_t^{\beta} . \tag{13}$$

This rate is clearly conditional on the previous soil quality level and the rotation index at time t. Note that when land is idle, rotation index, R_t takes the same value in every period.[7]

The measure developed in (13) can be used to assess the soil quality impact of holding land idle. The CRP generally requires that land be taken out of production for ten years. Accordingly, we evaluate the regeneration rate from a base soil quality of t-9 before program

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[7] The rotation index R_t is scaled to be positive before logarithmic transformation of the soil quality state equation. Before this scaling, $R_t = 0$ when land is idle.

participation but following a series of different rotations over the previous 20 years. Regeneration rates are thus calculated from the following equation:

$$r_t | (Q_{t-9}, R_{t-i} = k) = Q_{t-9}^{\alpha^{10}-1} \prod_{i=0}^{9} R_{t-i}^{\alpha^i \beta}, \text{ i=0, 1, ... ,9,} \tag{14}$$

where k is the N uptake amount when land is idle.

Figure 5 depicts the degree of soil quality improvement over time achieved by participating in a program that idles land. As before, only the relative comparisons offered in the figure are valid because of the ordinal nature of the soil quality measure. Consistent with conventional wisdom, the regeneration rate of the CCCCC (0) plot after a ten year retirement is greater than the regeneration rate among plots with a less intensive rotation history. Regeneration rates are strongly positive on the CCCCC (56) and CCCCC (168) and then less so on the other rotations without alfalfa. Note that the regeneration rates decrease when N-fixing crops such as alfalfa and soybean are included in the crop rotation, and they are quite dramatically reduced on rotations (e.g., CCCMM (168)) where alfalfa appears twice. These results underscore the potential of rotations to address at least some of the soil quality improvement objectives of soil conservation programs like CRP. Indeed, a more flexible program that incorporates the influence of previous crop rotations on soil quality regeneration rates could potentially achieve soil quality improvement objectives and also encourage more farmers to participate, by matching the fallow period with observed soil quality regeneration patterns.

Conclusion

This paper develops and implements a method for recovering an ordinal measure of soil quality from crop trials data using a simple recursive dynamic model. The soil quality measure estimates made in this paper used data from the University of Wisconsin's Lancaster crop trials, focusing on the corn productivity attribute of the soil and the impacts of rotation and fertilizer use on soil quality outcomes. However, the method could be applied readily to other attributes of the soil (its environmental remediation role for example, or its contribution to biodiversity) and to other practices and factors that shape the evolution of soil quality, such as tillage, other inputs, or biophysical characteristics of the locale (e.g., slope). The more variations in treatments available at a given crop trial, the more complete reflection the measure can provide of the interactions between soil quality and the relevant management practices and biophysical characteristics.

The estimation results were all consistent with values we would expect from a soil quality measure under different crop rotations and fertilizer applications, and dynamic estimates reveal some interesting relationships. For example, more intensive cropping reduces soil quality, *ceteris paribus*, but the dynamic soil quality effects of crop choice in a given period decline over time. N fertilizer and soil quality are shown to be substitutes in the short run; however in the long run, soil quality decline due to intensive corn cropping cannot be alleviated by higher N application rates. Simulations of soil quality evolution comparing distinct crop rotations and N fertilizer application levels revealed that crop choices, especially the use of legumes (such as alfalfa or soybean) could restore soil quality levels (as measured by productivity) quite quickly, and that continuous cropping of corn rapidly reduced soil quality even with high levels of N fertilizer application. The consistent fit between what we would expect from a soil quality measure and what is recovered from a dynamic model using crop trials data give reason to be optimistic about the potential value of this approach and a wider implementation using crop trials data from other sites. Such an effort would both take advantage of the other soil quality related outcomes and management practices captured in other experiments and the potential differences that might arise across distinctive soil types in the evolution of soil quality.

The broader social implications of improving and further applying this new method of recovering soil quality were only hinted at above through the example of land regeneration rates stimulated by land-idling policies like the Conservation Reserve Program. We showed, for example, that the soil quality regeneration rates on intensively used lands could be quite high, with most of the benefits achieved in a relatively short period of time. This means that in cases where the restorative effects of land idling rather than the conservation of highly erodible land are the primary goals, then reserve programs might not need such long time requirements. The results also showed that such programs could potentially obtain more soil quality improvement by using information on previous rotation histories to adjust the required length of fallowing periods, thus reducing the costs of conservation programs and encouraging broader participation.

The soil quality measure could be used for many other purposes, however. For one, it is conceivable that it could be used to improve the efficiency of operation of land markets, where uncertainty about long-run soil quality is likely to impede market transactions (Akerlof (1970)). Potential buyers could make use of readily observable information on the rotation history of individual fields, together with local information about soil types (perhaps at county level) to develop a means of comparing one field with others in the area. Thus, land pricing might be improved by the use of such a soil quality measure. Similarly, policies aimed at promoting better environmental outcomes could potentially make use of soil quality measures derived from test plots as a means of evaluating the expected impacts of farmers management practices. To the extent that society wants to reward or penalize farmers for outcomes associated with how they manage the soil quality on their properties, the type of measure developed here could potentially be of value if it were refined through further research work using crop trials data to be applicable to the relevant soil quality outcomes. The good news is that its value could be probed using existing data, and experiments could be augmented over time to build in new outcomes and management practices of social and scientific interest.

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Table 1. Estimated Parameters of Translog Production Function (Dependent variable = corn yield).

Parameter	Coefficient	Standard Error
Constant	-21.431	3.636***
α	0.647	0.029***
β	-0.058	0.024**
Log of N fertilizer (ln N)	0.097	0.038**
Log of July Precipitation (ln Prec)	2.080	0.456***
Log of July Growing Degree Days (ln G)	4.615	0.582***
$(\ln N)^2$	-0.005	0.005
$(\ln Prec)^2$	0.721	0.121***
$(\ln G)^2$	-.395	0.047***
(ln Q) (ln N)	-0.242	0.001***
(ln Q) (ln G)	-0.054	0.002*
(ln Q) (ln Prec)	-0.061	0.004***
(ln N) (ln G)	-0.003	0.003
(ln N) (ln Prec)	0.001	0.005
(ln G) (ln Prec)	-0.087	0.032***
Dummy1	-0.083	0.035**
Dummy2	0.262	0.088***
Dummy3	-0.683	0.099***
Dummy4	1.488	0.284***
Dummy5	0.288	0.036***
Dummy6	0.403	0.047***
Dummy7	0.126	0.037***
Dummy8	0.092	0.029***
Dummy9	-0.612	0.063***
Dummy10	-0.255	0.039***
Dummy12	-0.472	0.119***
Dummy1988	-0.717	0.047***

Note: Adjusted $R^2 = .5606$, number of observations = 1880. The symbols *, ** and *** denote significance at 10, 5, 1%, respectively. Dummy1988 was included in order to account for extremely dry weather conditions in 1988. The other dummies account for different corn varieties in the sample design. Corn output is measured in bu. ac^{-1} and N in lbs.ac^{-1}.

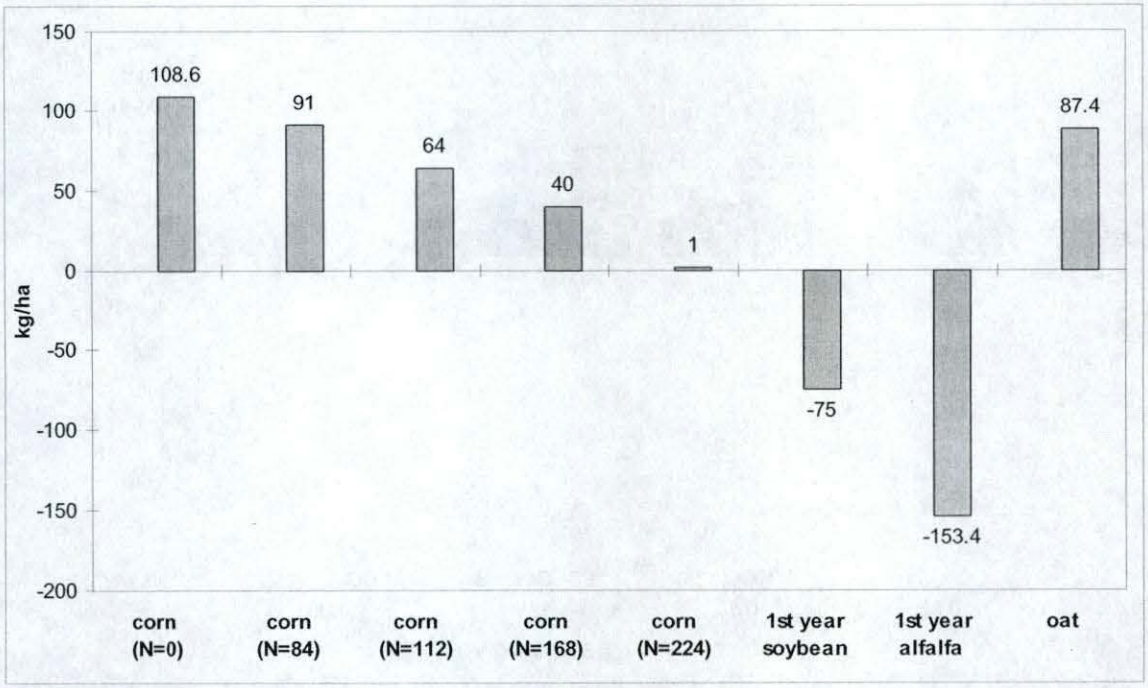

Figure 1. Net N uptake (kg/ha) by crop, accounting for carryover from previous year. N fertilizer is applied only to corn. Figures in parentheses (e. g., N=168) indicate previous year's N application levels.

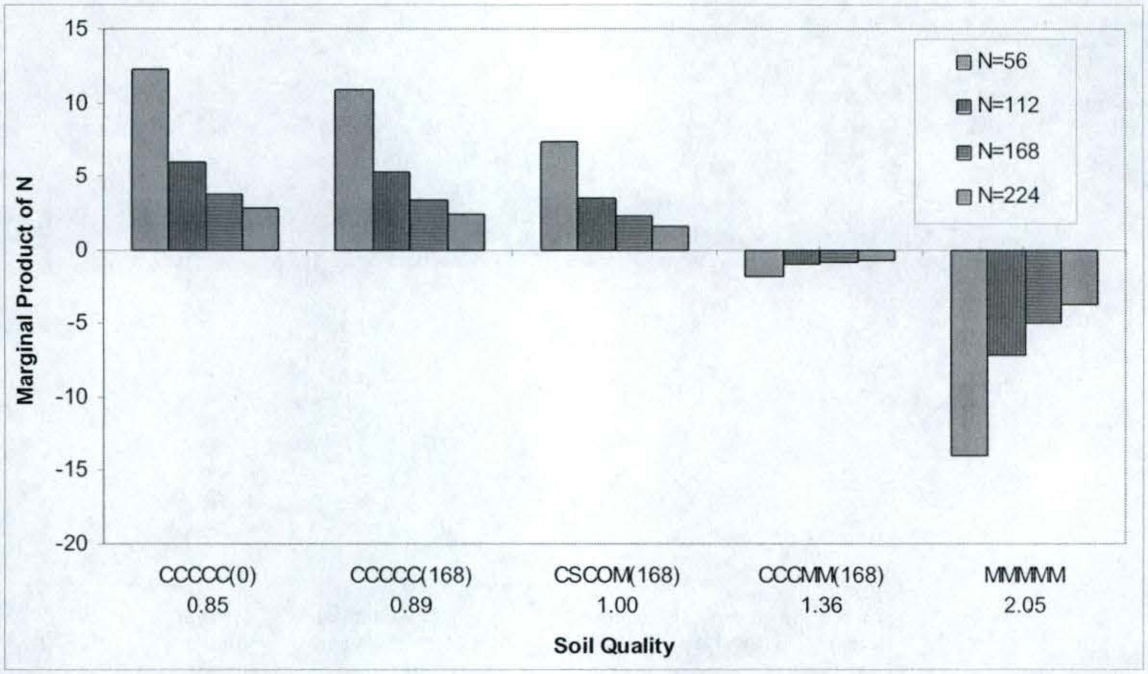

Figure 2. Relative marginal product of N fertilizer on corn conditional on soil quality. Data are grouped by rotation, and each group shows results for four levels of N application in the current year. In this and all subsequent figures, numbers in parentheses after each rotation (for example CCCCC (168)) show N application rates over the previous 20 years.

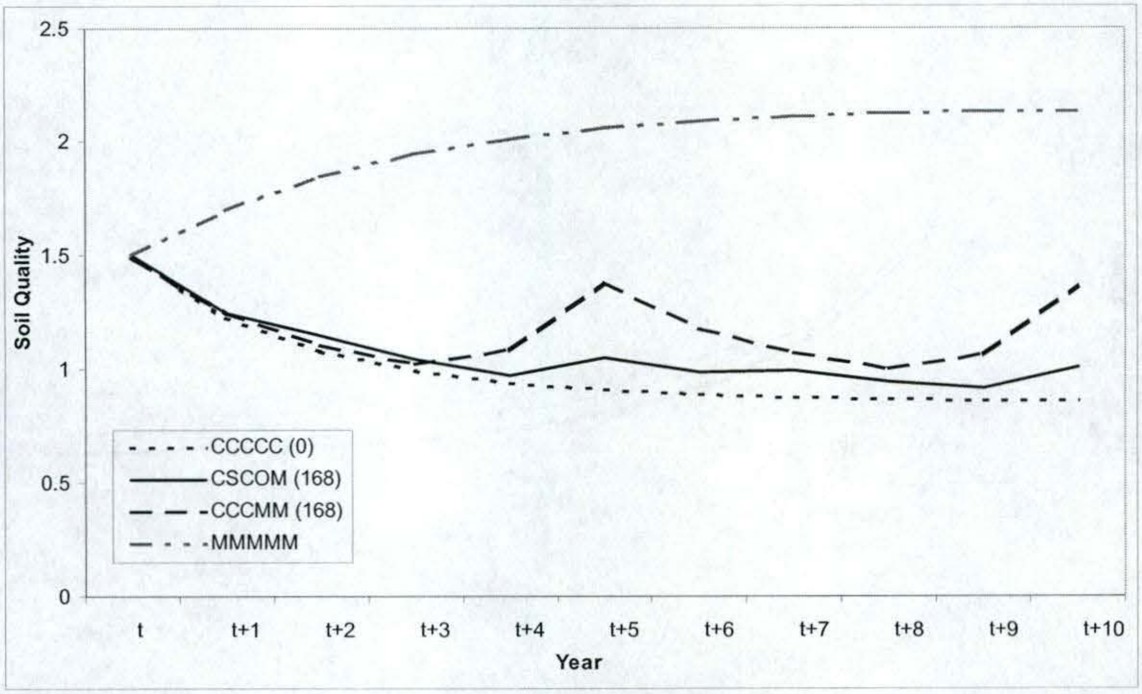

Figure 3. Evolution of soil quality conditional on crop rotation

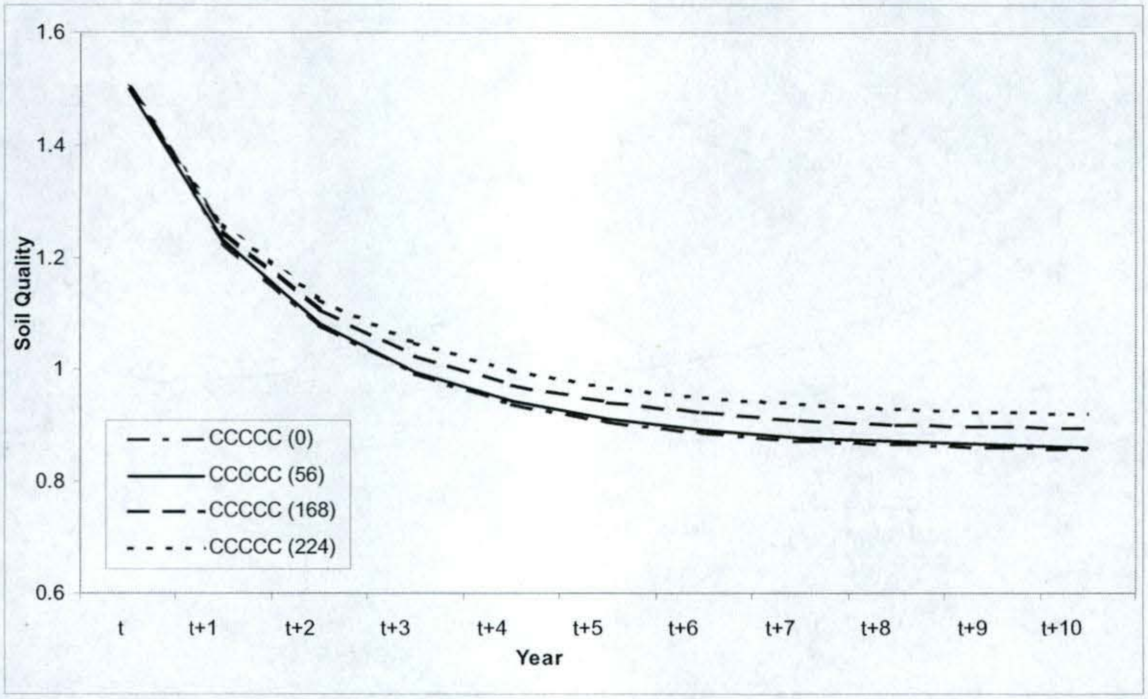

Figure 4. Evolution of soil quality conditional on N fertilizer. Data are for continuous corn rotations.

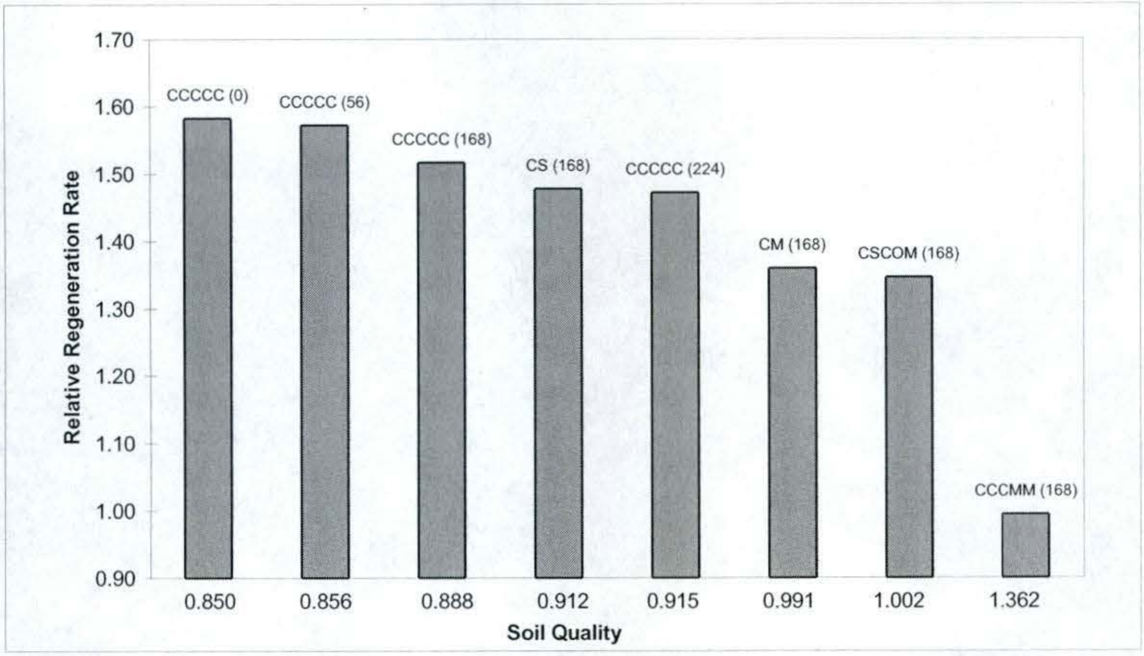

Figure 5. Relative soil quality improvement after 10 year's fallow. The x-axis shows initial soil quality (in year t-9). The y-axis shows regeneration rates, relative to a base case (CCCMM (168)=1).