Selected paper for presentation at American Agricultural Economics Association Annual Meeting, Salt Lake City, UT, August 1998.

Title:

The evolution of agricultural soil quality:

A methodology for measurement and some land market implications

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Key Words: soil quality, dynamic econometric method, land markets

Introduction

Environmental economists and policy makers often worry that farmers underinvest in soil

conservation, in part because inaccurate measurement of soil quality may prevent the complete

capitalization of soil-conserving investments into land prices (Gardner and Barrows; Blaine

et al.). If soil quality played no role in land prices then a farmer would rationally exhaust the

soil before offering a farm for sale. The limited observability of soil quality has both static

and dynamic dimensions; we explore both in this paper.

Although no party to a potential land transaction may have perfect information, the

capacity of the seller to accurately assess soil quality is greater than that of a potential buyer.

Asymmetric information about the properties of goods may prevent the efficient operation of

markets—the central insight of Akerlof's famous "market for lemons". However, agricultural

land markets differ from the markets for many other goods in that the *current* state of the land

is only part of the necessary information set. If land is degraded, for example by intensive

cultivation over a period of years, then potential buyers need to know not only the extent of the

degradation, but also the possible recovery paths and the costs of potential management

regimes along the path. Whether fertilizer or other inputs can serve as substitutes for soil

quality is part of the puzzle (Burt; Walker and Young; Taylor *et al.*), but in that case too the

answer depends on the underlying dynamics of soil quality depletion and recovery.

In this paper, we develop a method based on readily observable outcomes (in this

case, corn yields) that can explain current soil quality in terms of past management regimes

and predict its evolution under future regimes. Specifically, we apply two innovative

econometric approaches to crop trials data from a University of Wisconsin research station to

examine the effects of rotations and fertilizer use on the dynamics of soil quality and corn

yields. In the first, we estimate a random coefficients model of yield responses to nitrogen fertilizer and rotations. In the second, we explore the recursive properties of a dynamic structural model to recover an indirect but general measure of soil quality. The second approach enables an explicit analysis of the relationship between soil quality and the control variables (rotation and fertilizer), as well as attention to the soil quality-productivity nexus.

Both models reveal new information both about the soil quality effects of intensive cultivation and soil quality recovery paths. While N fertilizer is in the short run an effective substitute for soil quality, in the long run continuous corn cropping causes declines in soil quality that cannot be alleviated by higher N application rates. Moreover, rotations with nitrogen-fixing crops do provide a means for sustaining or recovering soil quality and yields. As a guide to the dynamics of soil quality recovery, we use the estimates from the two models to evaluate the speed at which soil quality returns to base levels under alfalfa following long periods of intensive cultivation.

The Lancaster Legume-Cereal Crop Trials

We use data from a 28-year legume-cereal rotation experiment. The series contains seven rotations applied on 42 plots. The rotations range from continuous corn (CCCCC) to corn-soybeans-corn-oats-alfalfa (CSCOM) to continuous alfalfa (MMMMM) (for further details see Kim *et al*.).

N is applied only to corn and at four distinct levels (0, 50, 100, and 200 pounds per acre) on sub-plots. The only variations in management practices are in rotation and N fertilizer use (although new seed varieties are tried in different years), so our study focuses only on how these practices affect the dynamics of soil quality and corn yields.

Because N is applied only to corn, measures of rotation and N use are strongly collinear. To resolve this problem, we combine rotation choices and N levels into a single rotation-fertilizer index. Constructing this index is facilitated by available estimates of N uptake and carryover (Vanotti and Bundy (1994, 1995) and Vanotti, Leclerc, and Bundy). In the case of N-fixing legumes, nitrogen uptake is negative, and in the case of N carryover from previous fertilizer applications, that value is also subtracted from the index. By construction, if no crops were planted on a given plot the rotation-fertilizer index for that plot and year would be zero. We use these cardinal estimates to construct an ordinal ranking of rotation and fertilizer applications with its highest value in a rotation of corn and no fertilizer, its lowest value in an all-alfalfa rotation.

A Random Coefficients Model of Yields, Rotations, and Fertilizer Use

We first examine the short- and long-term effects of crop rotations and N use on corn yields using a random coefficients model (RCM) (Swamy; Hsiao). Previous studies have used RCM approach to obtain improved estimators in the presence of unobserved sources of variation such as rainfall or pests (e.g., Smith and Umali). However, the RCM is a powerful and parsimonious technique to control for *known* fixed effects like past crop rotations that might have plot-specific impacts.

The RCM specification for corn yield response is given in equations (1) and (2):

$$\mathbf{y}_i = \beta_{0i} \mathbf{N}_i + \mathbf{X}_i \boldsymbol{\beta}_1 + \boldsymbol{\varepsilon}_i, \quad i = 1,..., n, \tag{1}$$

$$\beta_{0i} = \mathbf{Z}_i \boldsymbol{\gamma} + \eta_i, \tag{2}$$

where $\mathbf{y}_i$ is a vector of time-series observations on corn yields for plot i, $\mathbf{N}_i$ is a vector of time series observations on the level of N fertilizer application for plot i, $\mathbf{X}_i$ is a matrix of time

series observations of exogenous variables. $\boldsymbol{\beta}_1$ is a vector of parameters, and $\boldsymbol{\varepsilon}_i$ is a vector of uncorrelated random variables with zero mean and variance-covariance matrix $E\boldsymbol{\varepsilon}_i\boldsymbol{\varepsilon}_j^{'} = \sigma_{ij}^2 \mathbf{I}_T$.

β_{0i} is a random coefficient that varies according to (2). $\mathbf{Z}_i$ and $\boldsymbol{\gamma}$ are vectors of known and unknown constants, respectively. η_i is an unobservable random variable with zero mean and variance-covariance matrix $E\eta_i\eta_i^{'} = \lambda_i$ and $E\eta_i\eta_j^{'} = 0$. We assume that $\boldsymbol{\varepsilon}_i$ and η_i are uncorrelated with each other. In this specification plot-specific variability in the marginal effect of N fertilizer on yield, i.e., the heterogeneous yield response resulting from soil quality differences, is measured by the random coefficient, β_{0i}. The key variables that need to be further specified are in $\mathbf{X}_i$ and $\mathbf{Z}_i$. 1The matrix $\mathbf{X}_i$ includes variables representing the short-term and long-term effects of alternative crop rotations. We develop three rotation indexes for each year t and each plot i, based on the N uptake information discussed above. RI1, the current value of the rotation index, equals the N uptake of the current period's crop plus the N fertilizer carryover. RI5, a five year moving summation of RI1, provides a measure of the short-term rotation flow. CRI, the cumulative summation of RI1, is constructed to capture the long-term rotation effect. The vector $\mathbf{X}_i$ contains a constant term plus RI1, RI5, and CRI, the mean deviation over T years for July Growing Degree Days (GDDDEV), the mean deviation over T years for July precipitation (PRECDEV), dummy variables for different corn varieties (D1-D10, D12) used in the experiments, and a dummy variable (Dummy1988) for a drought year, 1988. $\mathbf{Z}_i$, consists of a constant, $ZRI1_i$, the mean value in time t over all previous time periods of the current rotation index (RI1), and $ZRI5_i$, the mean value in time t over all previous time periods of the five year rotation index (RI5). $\mathbf{Z}_i$ thus characterizes plot-specific characteristics in terms of initial differentials or those that might arise as a function of past crop choices.

Combining equations (1) and (2), the full specification is given by:

$$\mathbf{y}_i = \mathbf{W}_i\boldsymbol{\gamma} + \boldsymbol{\beta}_1\mathbf{X}_i + \mathbf{u}_i , \qquad\qquad (3)$$

where $\mathbf{W}_i = \mathbf{N}_i\,\mathbf{Z}_i$, $\mathbf{u}_i = \mathbf{N}_i\,\eta_i + \boldsymbol{\varepsilon}_i$ and $E\mathbf{u}_i\mathbf{u}_i' = \boldsymbol{\Omega}_i = \mathbf{N}_i\lambda_i\mathbf{N}_i' + \sigma_i^2\,\mathbf{I}_T$. The GLS estimates of $\boldsymbol{\beta}_1$ and $\boldsymbol{\gamma}$ are shown in Table 1. The rotation history effects (RI1, RI5 and CRI) are highly significant and have expected signs. In particular, the negative signs and the declining size of the RI coefficients indicate that if an N-demanding crop such as corn is planted at time t, then a decrease in corn yield is expected at times t+i, and the effects of crop rotation at time t on corn yields at time t+i diminish as i increases.

Table 1. Estimation of Random Coefficients Model for the Corn Production

Parameter	Coefficient	Standard Error
Constant	121.037	2.390***
RI1	-7.503	0.547***
RI5	-2.204	0.524***
CRI	-0.999	0.185***
GDDDEV (deviation from the mean)	-0.321	0.0342***
PRECDEV (deviation from the mean)	-4.767	0.895***
ZIDEN (constant)	0.0245	0.011**
ZRI1	0.125	0.258
ZRI5	-0.0224	0.057

Note: Adjusted R^2 =0.965, number of observations = 1880. The symbols *, ** and *** denote significance at 10, 5, 1%, respectively. Variety and 1988 dummy variable estimates are not reported. Corn output is measured in bu. ac^{-1} and N in $lbs.ac^{-1}$.

By substituting $\hat{\boldsymbol{\gamma}}$ into equation (2), we can recover the random coefficient β_{0i}, which represents the marginal effect of N fertilizer application on yield conditional on plot-specific characteristics. The results show that the marginal contribution of N fertilizer has the highest value in the case of a continuous corn rotation, and that its marginal contribution to yield

declines as N-fixing crops such as alfalfa are included in the rotation. In the continuous

alfalfa rotation, the marginal yield effect of N is negative. This result is supported by

experimental data showing declining corn yields at high fertilizer levels on plots with two or

three successive alfalfa rotations.

The results in Table 1 can also be used to predict yield conditional on crop rotations

and N fertilizer application, and thus to shed light on the substitutability of N fertilizer and

soil quality. Figure 1 portrays the simulated effects of rotation on predicted yields at four

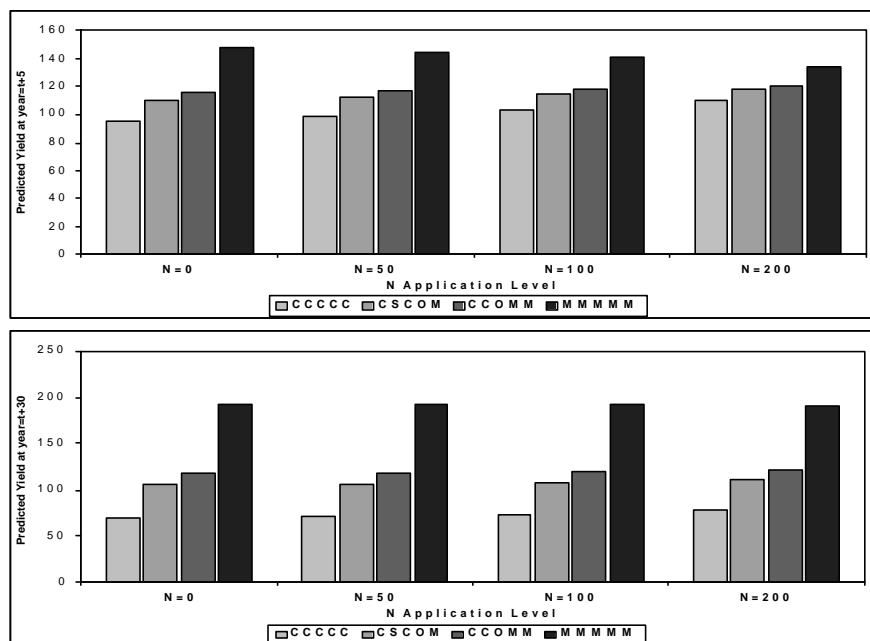different N levels after 5 and 30 years of distinct rotations.

Figure 1. The effects of N application on predicted yields after 5 and 30 years of given rotations.

One can easily see that N fertilizer is at least a short-run substitute for land productivity: the

year 6 yield difference between continuous corn and other rotations is substantially smaller at

higher N application levels. Yet, as the second panel reveals, higher N application rates

cannot compensate for productivity losses associated with long-term crop rotations. Figure 1

casts doubt on the view that N fertilizer can act as a substitute for soil quality in the long run.

A Dynamic Structural Model for Recovering a Measure of Soil Quality

In this section we develop a recursive dynamic model of corn production and use it to recover an explicit measure of soil quality. This enables us to incorporate soil quality as a state variable in dynamic economic analyses of land productivity, land markets, and conservation programs.

Let $f(\cdot)$ denote a crop production function and $g(\cdot)$ the function that governs the state equation for soil quality. Then the nested production function can be written as:

$$Y_t = f(Q_t, N_t, Prec_t, G_t) \text{, and} \tag{4}$$

$$Q_t = g(Q_{t-1}, R_{t-1}), \tag{5}$$

where Y_t is (again, corn) yield at time t, Q_t is the state of soil quality at the start of period t, N_t is the level of N fertilizer application, $Prec_t$ is average July precipitation, G_t is July growing degree days at year t, and R_{t-1} is the rotation index variable at year t-1. The specification of soil quality state equation reflects the recursive nature of soil quality evolution; i.e., soil quality at a certain period cannot be entirely determined by choosing the level of control variables in the previous period.

To estimate this model we substitute equation (5) into (4) to obtain the nested production function:

$$Y_t = f(g(Q_{t-1}, R_{t-1}), N_t, Prec_t, G_t). \tag{6}$$

The next step is to choose the functional forms of $f(\cdot)$ and $g(\cdot)$. Because the elasticity between soil quality and N fertilizer in (4) is a key issue, the functional form for $f(\cdot)$ is chosen seeking

minimal *a priori* restrictions on the substitutability of these two variables. The translog

production function satisfies these requirements. The function f(·) then becomes

$$\ln Y = a_0 + \sum_i b_i \ln \mathbf{X}_i + \frac{1}{2} \sum_i \sum_j b_{ij} (\ln \mathbf{X}_i)(\ln \mathbf{X}_j),\qquad(7)$$

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

Given the translog assumption, a Cobb-Douglas structure for g(·) gives the necessary

linearity in parameters that leave the model tractable. As is well known, the Cobb-Douglas

structure imposes strong restrictions on the elasticity estimates of the governing state equation,

an issue we explore below. After logarithmic transformation and successive substitution of

Q_t, the state equation g(·) becomes

$$\ln Q_t = \sum_{j=1}^{24} \alpha^{j-1} \beta \ln R_{t-j} + \alpha^{24} \ln Q_{t-24},\qquad(8)$$

where Q_{t-24} is normalized to unity to reflect initial conditions when the sample is large and α

< 1. The final step involves substituting (8) into (7) 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.

Before undertaking the estimation, it is necessary to resolve one important

identification problem associated with the nested production function. This can be done by

setting $b_1 = 1$ in equation (8).[1] Note that this normalization changes the *absolute* value of the

coefficients of the nested production function, it leaves their *relative* values unaffected,

allowing us to estimate an ordinal measure of soil quality.

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[1] For the details, see Kim et al.

The nested production function is estimated using NLS (Non-linear Least Squares)

method with variety and 1988 dummies as before. The results (Table 2) have the expected

signs, a high level of significance, and explain 56% of corn yields variation.

Table 2. Estimated parameters of Translog Production Function (dependent variable = corn yields)

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***

Note: Adjusted R^2 = .5606, number of observations = 1880.   The symbols *, **
and *** denote significance at 10, 5, 1%, respectively. Corn output is measured
in bu. ac^{-1} and N in lbs.ac^{-1}. Variety and 1988 dummy variable estimates are not
reported.

The estimate of α reflects the dynamic effects of crop rotation on soil quality over time, and

its value (0.647) means that the effects will decrease as time elapses. The estimate of β is -

0.058, and confirms the expectation that soil quality decreases with more intensive

cultivation. Other coefficient estimates provide further insights. In particular, the negative

and significant coefficient of the interaction term of soil quality and N ((ln Q)(ln N)) indicates

an inverse relationship between the marginal productivity of N and soil quality (as in a reduced-form estimation).

Whether the findings from the two models has relevance to the performance of land markets depends essentially on two factors, the degree to which soil quality information is imperfectly observed by buyers, and the length of time required to recover soil quality. Our two models give us the capability to explore this latter question.
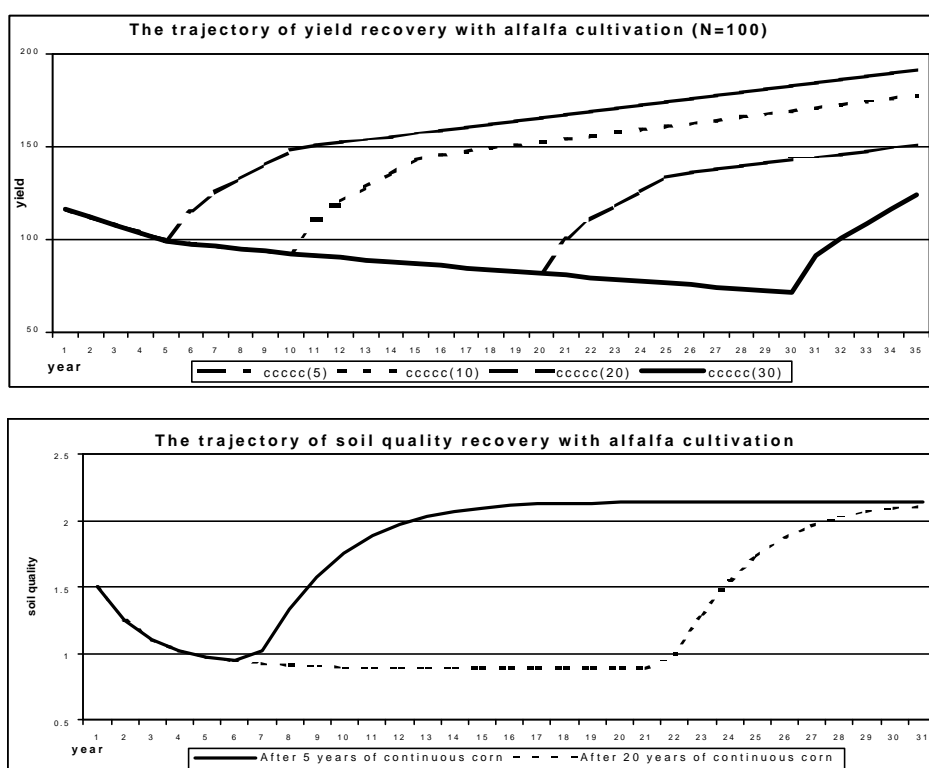

Figure 2. The trajectories of yield and soil quality recovery through the use of alfalfa

In Figure 2, in the upper graph, the estimation results from the RCM are mapped: these show declining yields over time under continuous corn, and progressively longer yield recovery periods. These suggest that knowing a lengthy history of management practices could help buyers to evaluate potential land purchases. The second graph maps out the recovery of soil quality using the dynamic structural model. Soil quality takes about three

years to recover, so that less information on key control variables would be required to signal underlying soil quality to other land market participants.

There is clearly a fundamental difference between the two trajectories in terms of their speed of decline. The Cobb-Douglas structure of the $g(\cdot)$ function and the estimated value of α from the dynamic structural estimation provide the basis for the rapid decline and then flat portion of the trajectory, while the less restrictive RCM functional form provides a more intuitive depiction of declining yields over time that then take progressively longer periods to regenerate. Two basic conclusions emerge. First, the more rigid structure needed to keep the dynamic model econometrically tractable may impose restrictions that limit the uses of the results for extensive modelling simulations. Second, both models show that missing information on soil quality could be important, in that the recovery time for soil quality regeneration following continuous corn cultivation could be economically important.

Conclusions

In this paper, we first developed a random-coefficients model of the relationships among crop rotations, N fertilizer application and corn yield. Estimation results showed that the marginal contribution of N fertilizer varies with a different rotation history. Extrapolations of the estimation results provide empirical evidence against N fertilizer as a substitute for corn-intensive rotations in the long run. We then developed a structural-form model that employs soil quality directly as one of the arguments in the production function in order to measure relationships among crop rotation, N and soil quality. We find an inverse relationship between soil quality and the marginal productivity of N fertilizer. The results also show that soil quality will decrease substantially under continuous corn, but that it can be maintained at a steady level when alfalfa is included in the rotational sequence.

Combined, the models provide convincing evidence that while N may provide a short-term substitute for soil quality, it cannot in the long run. Yet, rotational choices do provide such an option for maintaining soil quality and land productivity and also the means for restoring the quality of land that has been intensively cropped. The recovery time, however, depends on the history of land use choices, which makes knowledge of the evolution of soil quality potentially important to buyers.

By providing information on a key state variable, our soil quality measure could be used in a wide variety of dynamic models of farmer behavior. Of course, any such modelling effort must confront the issue of soil quality observability and its effects on farmer's land use decisions. In particular, the asymmetric distribution of information about soil quality may influence the operation of land markets, and thus, through the price of land, condition farmers' optimal land use decisions. More generally, our analysis motivates an extension of the Akerlof model in which the properties of goods evolve dynamically over time, thus influencing the emergence and functioning of markets (Kim).

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