The Economics of Mining Soil Fertility:
A Dynamic Modeling Approach.

by
Patrick A. Jomini
and
J. Lowenberg-DeBoer

The authors are graduate assistant and assistant professor Department of Agricultural Economics, Purdue University, W. Lafayette, IN 47907.
ABSTRACT

Conditions are identified under which soil fertility depletion may be a desirable management practice. Dynamic programming is used to evaluate strategies based on extension recommendations. Fertility mining is advisable when input prices are expected to fall, capital is constraining or output prices or tax rates are expected to rise.
The economics of mining soil fertility: A dynamic modeling approach.

1. Introduction

Using up soil nutrients by repeated cropping without adequate fertilizer to at least replace minerals lost in crop removal is often referred to as "mining soil fertility". In the agronomic, and also in the economic literature, mining soil fertility is often seen as a bad farming practice that may increase short run returns, but at the cost of reduced long run productivity and profitability. It is suggested that soil fertility is mined by farmers who are ignorant of the long term consequences of this strategy or by producers with severe financial constraints who have few other choices. The alternative view is that soil fertility is like a bank account that is built up or drawn down as the need arises. The goal of this study is to identify conditions under which mining soil fertility is a rational economic decision. Fertility management decisions have acquired new importance in the 1980s because low crop prices are forcing many farmers to search for ways to cut costs. Mining soil fertility is a frequently mentioned possibility, but this strategy has not been investigated within a formal framework. Identifying when farmers might cut fertilizer use below the maintenance needs as part of a strategy to maximize expected long run profits is of interest to farmers, lenders and input suppliers.

This paper includes both an analytic section and an empirical example. After a brief review of the literature, a dynamic programming model of a farmer's phosphorus application decisions is developed and used to identify scenarios under which soil fertility mining might be a candidate for optimality. A dynamic framework is necessary for the soil fertility mining question because the issue is long term productivity and profitability. Because of its relative immobility in the soil and because only a small part of the total
soil phosphorus is available to plants in a given season, phosphorus is a good example of plant nutrients which persist in the soil and contribute to long term soil fertility. A similar model could be used for potassium, calcium and other soil nutrients that carry over. An empirical application of the model to Indiana corn production is used to determine the relevance of fertility mining under observable parameter values.

2. Previous Research

The general framework for economic choices in soil fertility management is well developed. Dillon outlines the theoretical analysis. When nutrients carry over from previous seasons, the problem becomes choosing application rates and timing to maximize the utility of the stream of income from cropping. Because of the dynamics, this becomes a very complex problem and researchers have sought simplification which would allow concise analytic statements about fertility management and empirical estimates of optimal strategies.

The most common simplification is that the producer is assumed to maximize the expected net present value of profit. In that case, the general decision rule is to apply the fertilizer so long as the net present value of returns from the marginal application exceed the fertilizer cost. Kennedy et al. further simplify the problem by assuming that fertilizer carryover is proportional to the stock of that nutrient in the soil, that the optimal application is always positive, that input and output prices are constant and that the capital constraint is not binding. The decision rule derived from their dynamic programming model consists of applying, in each period, the amount of fertilizer which gives the profit maximizing yield in the current season, whatever the initial fertility level. Kennedy discusses the mathematical complications of allowing zero level applications in the Kennedy et al. model, but does
not analyze the economic consequences of the no application strategy. Lanzer and Paris analyzed nitrogen, phosphate and potash use on wheat and soybeans in Brazil with a multiperiod linear programming model. Their model permits a no application strategy but under the constant price, no capital constraint and relatively low initial fertility conditions they analyzed, some application was optimal. Stauber, Burt and Linse use a dynamic programming model similar to that developed by Kennedy et al., except that they allow the carryover to be stochastic and their numerical model of nitrogen application on semiarid grassland permits a zero application strategy. Because of the stochastic carryover equation no general decision rule is derived. Their numerical results indicate that under certain circumstances a no application strategy can be optimal.

3. An economic model of fertilizer carry-over

The model outlined here starts from the analysis developed by Kennedy et al. but relaxes the assumption of constant prices and permits zero level application. For simplicity, a continuous cropping pattern is considered. Two inputs are assumed to compete for financial resources. They are phosphorus (P) fertilizer which carries over into future production periods, and nitrogen (N) fertilizer, assumed to affect only current production. A response function (F) assumed known to the decision maker and fixed over time links plant-available P and N to expected yield (Y) in a cropping season:

$Y = F(SP, SN)$

where the derivatives $F_i > 0$, $F_{ii} < 0$ and $F_{ij} > 0$ for $i \neq j$ (positive decreasing returns and technical complementarity) and SP, SN are plant available P and N nutrient levels respectively.
Under the assumption that N does not carry-over, the current season’s application (AN) is the only source of N. A constant of proportionality ($\Theta n$) accounts for nutrient losses due to leaching, denitrification, and application inefficiencies, so that the amount of N available to the plant each period is:

\[ SN = \Theta n \times AN \]

In the case of P, previous applications account for a large part of the plant-available nutrient stock. This stock (TP) is measured by a soil test (e.g. a Bray P1 test). An equation of motion describes the evolution of nutrient availability each period:

\[ TP_{t+1} = \delta p \times [\Theta p \times AP_t + TP_t] \]

where $\delta p$ is the proportion of P left in the field – losses are due to erosion and plant uptake (exogenous for simplicity) – and $\Theta p$ is the proportion of applied P available for plant uptake. In other words, $\Theta p$ converts the applied P into a soil test equivalent. Carryover equation (3) is equivalent to that used by Kennedy et al. Its form is slightly different because it is expressed in soil test units, not fertilizer units. The carry over proportion $\delta p$ is the same as the $V$ used by Kennedy et al.; it is assumed constant and independent of weather characteristics (erosion). The term in brackets is the amount of P that is available to the crop at period $t$ (SP).

The farmer is assumed to maximize the present value of expected net income flows generated by crops grown on one acre over a time horizon of length $m$. This objective can be stated in a recurrence relation in which the decision maker maximizes current income, dependent on an initial level of soil P, assuming that all future decisions are taken optimally:

\[ ES_t(TP_t) = \text{MAX}_{AP_t, AN_t} \left[ \alpha_{p_t} Y_t - (\gamma T_t + \gamma P_t \times AP_t + C) \right] (1 - \tau_t) + \alpha ES_{t+1}(TP_{t+1}) \]
where ES is the expected stream of income attainable with an initial soil fertility level of TP, \( \alpha = 1/(1+r) \) is the after-tax discounting factor, \( \pi \) is the expected output price based on information at \( t-1 \), \( r_n \) and \( r_p \) are the expected N and P fertilizer prices at the beginning of a period, C stands for all other expenses - which are held constant - and \( \tau \) is the expected tax rate. Yield and price distributions are assumed to be independent.

In order to specify the endpoint (transversality) condition, the value of soil fertility at the end of the planning period is estimated as the cost of an equivalent amount of fertilizer applied at that time:

\[
(5) \quad ES_{m+1}(TP_{m+1}) = r_p \pi_{m+1} = (1+\tau_{m+1}) (TP_{m+1}/\theta_p)
\]

Relevant constraints include non-negativity (\( AN, AP \geq 0 \)) and capital requirement constraints for each period \( t = 1 \ldots m \):

\[
(6) \quad \beta n \pi AN + \beta p \pi AP \leq Kf
\]

where \( \beta n \) and \( \beta p \) are money capital requirement coefficients as defined by Vickers and \( Kf \) is the amount of capital available for fertilizer expenses.

4. Best operating conditions

The Lagrangian method is used to derive best operating conditions; the problem can be restated as:

\[
(7) \quad L_t(AN_t, AP_t, \mu_t) = ES_t(TP_t) + \mu_t(Kf_t - \beta n\pi AN_t - \beta p\pi AP_t)
\]

where \( L \) and \( \mu \) are the Lagrangian function and multipliers respectively. The later is interpreted as the marginal value of capital available in period \( t \).

With a concave response function sufficient conditions exist for a maximum. Setting derivatives of the Lagrangian with respect to its arguments equal to zero yields the following best operating conditions:

\[
(8) \quad (1 - \tau_t)\pi F_{SN} \pi n - r_n \pi _t - \mu_t \beta n_t = 0
\]

\[
(9) \quad (1 - \tau_t)\pi F_{SP} \pi p - r_p \pi _t + \alpha [dES_{t+1}(TP_{t+1})/dAP_t] - \mu_t \beta p = 0
\]
\[ \text{(10) } K_t - \beta n_t AN - \beta p_t AP = 0 \]

for \( t = 1 \ldots m \), where \( F_i \) are the derivatives of the response function with respect to its arguments, and other variables are as defined previously.

The second bracket in equation (9) reflects the effect of current P application on the value of soil fertility at the end of the current period. Starting from the endpoint condition and substituting TP backward, this effect can be expressed as:

\[ \text{(11) } \frac{dE_{t+1}}{dP_t} = \theta P \sum_{j=t+1}^{m} [(1 - \tau_j) * \alpha^{j-t} * \delta^{j-t} * \pi_j * F_{SP}] \\
+ \Gamma P_{m+1} * (1 - \tau_{m+1}) * \alpha^{m-t+1} * \delta^{m-t+1} \]

that is, the change in the value of soil fertility due to a change in the application rate of P equals the sum of the discounted effects of the change in the current application on future income, including the residual value of fertility at the end of the planning horizon.

In order to interpret marginal conditions (8) and (9), it is easiest to start with a case in which capital is not constraining (i.e. \( \mu = 0 \)).

Marginal condition (8) requires that in each period N be applied up to the point when after-tax marginal revenues equal marginal factor costs. Equations (9) and (11) highlight the importance of carryover in P related decisions: current marginal factor cost must equal the sum of current marginal revenue and the present value of future income resulting from the current P application.

In general, the optimal demand for P or N will depend on the initial soil test, all prices, and the response function parameters. Because of the assumed technical complementarity in production, each input's price affects the demand for the other input. Future and current input prices affect the demand for inputs because the marginal productivity of P in any period (\( F_{SP} \)) depends on both N and P levels in that period, which in turn depend on input prices from that period to the horizon. When capital is not constraining, if
at least a maintenance P application is made in every period, the interior solution holds in all future periods and an analytical equation can be derived by solving $2m$ equations simultaneously ($2$ equations for each period for $m$ periods). If the no application strategy is permitted, there is no general analytic solution because periods when the application falls to its limit level (zero) cannot be predetermined, as they depend on parameter values. The marginal conditions do, however, suggest some candidate strategies and among these the no application option may prove desirable in certain cases.

For example, if the initial soil fertility is high given current prices, the marginal productivity of applied P ($\theta pF_{SP}$) will be low and the present value of the marginal value product ($\pi t\theta pF_{SP}$) may be lower than the price of P at any application level, suggesting a no application strategy. This analysis, like previous work, indicates that higher output prices and lower input prices increase the optimal level of soil fertility. This can be seen by noting that in long run equilibrium with constant prices, the marginal productivity of P is the same in every period because the soil test level at the beginning of each period and the choice of N are the same. If the output price increases or input price decreases, a lower level of the marginal productivity (i.e. a higher application rate) is required to maintain the marginal equality. Hence, if a farmer were in long run equilibrium at some high output price level and output price dropped dramatically, or input prices rose, the new long run equilibrium soil fertility level would be lower and a no application strategy might be followed until soil fertility decreased to its new optimal level.

In the previous example, the no application strategy results from the soil's fertility level becoming sub-optimal with a change in the farmer's economic environment. Other examples in which a no application strategy may
be favored include an expected increase in the tax rate, or a drop in
capital availability. In the case of an expected tax increase, the future
effects term in equation (9) is decreased, and, under constant prices,
current application must decrease (i.e. $F_{SP}$ increases) to maintain the
marginal equality. This corresponds to a strategy which draws down soil
fertility to increase income in the current low tax period and rebuilds fertility
later when the after-tax cost of fertilizer is lowered by the higher tax
rate. This strategy is favored by a relatively low rate of discount.

If capital is in limited supply in any period, $\mu$ is strictly positive.
In order to maintain equalities (8) and (9) with the input complementarity and
decreasing marginal returns assumed in $F$, optimal amounts of N and P to be
applied must be lower than in the case of non-constraining capital. At high
soil P levels, the marginal loss from reducing P application is small, since
carryover is a major source of current plant available P. On the other
hand, reducing N application may significantly reduce yield since current
application is the only source of this nutrient. The relative effects on
yield of nutrient application depends ultimately on the behavior of the
nutrients in the soil, as reflected by parameters $\theta_p$, $\theta_n$ and $\delta_p$, and their
interaction effects. If the soil P level is adequate and capital resources
are temporarily constraining, the solution may be to draw temporarily on P
reserves, in order to maintain an adequate supply of N even in the face of a
binding financial constraint.

In general, any change in economic conditions which results in a lower
fertility level being optimal favors a mining strategy in the short run to
achieve the new long run equilibrium fertility level. The qualitative results
presented in this section indicate possibilities for mining P in the short
run as an economically viable fertilization strategy available to farmers especially when initial soil P reserves are relatively high.

5. A numerical application

A dynamic programming (DP) model for continuous corn production in Indiana was developed from fertilizer recommendations published by Purdue University's cooperative extension service (Spies and Mengel) and other commonly used P management strategies. DP provides an efficient way of enumerating best choices among a wide variety of operating conditions and outcomes resulting from these choices. Assuming that farmers maximize the sum of present and future net after-tax income, optimal management strategies are identified from among the set of options.

The response to N and P applications is modeled in a two-input linear response and plateau function (see Anderson and Nelson, Lanzer and Paris for details) with a maximum expected yield of 135 bu/acre. Other assumptions for agronomic parameters are: \( \theta_p = 1/9 \), \( \theta_n = 1 \) (no N losses); \( \delta_p \) only reflects plant uptake, and is yield dependent. The DP model covers a horizon of twelve years or three decision periods of four years each. Each period, the farmer is assumed to decide on a fertilization strategy which affects the next four years. The strategies for P include 1) maintenance applications, 2) applications recommended by Spies and Mengel to obtain a fertility level corresponding to a target yield within 4 years, 3) a heavy initial application followed by 3 years of maintenance, and 4) no application. N applications range from 120 to 230 lbs/a, depending on the yield goal. The discount rate is 12% for strategies A through D, and 30% in E and F; other costs net of government payments are $100 throughout. Money capital coefficients are
assumed to be the same as fertilizer prices. Economic parameter values for various scenarios are listed in Table 1.

Results for all fertility levels for a baseline case are presented under letter A in Table 2. Starting soil P levels vary from very low, to very high (5 to 55 lbs/a). For each decision period of 4 years, soil P, application strategy and minimum yield attained in that period are listed. Under the assumed agronomic and economic conditions, P reserves must be drawn down (mined) in the high fertility soil, and built as fast as possible in the low fertility soil to reach an optimal soil P level (35 lbs/a) at which the maximum yield is obtained. To increase soil fertility, heavy initial application is preferred as long as capital is available; otherwise, the maximum compatible four year build-up rate is used.

Scenarios B, C, D, E, F show other examples of situations under which fertility mining in the first period is part of an optimal strategy. Under B, a decrease in the price of P is expected in year 5. Mining is advisable even on medium fertility fields in the first 4 years as P can be applied cheaper in the following periods to replenish soil P reserves. The higher net present value (NPV) results from the sharp drop in costs.

Under C, the price of N is expected to decrease. The wealth maximizing choice is to forego P application in the first years (when N is expensive) in order to maintain an adequate supply of N. A similar result is obtained when capital is temporarily constraining (scenario D). In scenario E, an expected increase in the price of corn combined with a high discount rate provides incentives to delay P fertilization in an attempt to transfer income from future periods to the present. A similar interpretation is applicable to scenario F under which an increase in taxes is expected.
6. Conclusion

Fertilizer recommendations are usually geared toward maintaining high soil P levels through regular maintenance applications. This paper shows that conditions can be identified under which soil fertility mining may prove an adequate strategy in the short run to adapt to temporary constraints or as a means of transferring income from the future to the current period.
7. References


Dillon, J.L.: The analysis of response in crop and livestock production.


### TABLE 1: ECONOMIC PARAMETERS FOR VARIOUS SCENARIOS

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### TABLE 2: BEST FERTILIZATION STRATEGIES UNDER VARIOUS SCENARIOS

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### TABLE 3: BEST FERTILIZATION STRATEGIES UNDER VARIOUS SCENARIOS

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