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POPULATION GROWTH, SOIL FERTILITY, NONCONVEXITIES, AND AGRICULTURAL INTENSIFICATION

by

Jeffrey A. Krautkraemer

Energy and Natural Resources Division
Resources for the Future
1616 P Street, N.W.
Washington, D.C. 20036

and

Department of Economics
Washington State University
Pullman, WA 99164-4860

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Abstract

This paper presents a renewable resource model of soil fertility with a nonconvexity in the net benefit function. In this setting, recurring cycles of cropping and fallow can be the optimal soil management strategy. The model is used to illuminate the Boserup discussion of agricultural development in which population growth is a precondition for agricultural intensification, defined as an increase in the frequency of c

Previous formal models of the Bo[illegible] hypothesis have focused on the land-labor ratio rather than the frequency of cropp[illegible] they have not directly incorporated the dynamics of soil fertility. These models assume a convex production technology and, in general, they are not particularly optimistic about the prospects for agricultural development without technological progress. In the absence of an improvement in agricultural technology, the average productivity of labor declines and either per capita consumption must fall or the number of hours worked must increase. In either case, population growth results in a decrease in well-being and the analysis has a Malthusian flavor.

This paper explicitly models the dynamics of soil fertility and demonstrates that nonconvexities in the production technology are an important element of the use of long fallow periods for soil management. Indeed, nonconvexities are necessary for a non-continuous farming strategy to be optimal. As population grows, and the demand for food increases, the importance of the nonconvexity diminishes and it becomes economical to farm the land more frequently. The periods of fallow become shorter and eventually a continuous farming strategy is optimal.

Since a nonconvexity in the production technology is necessary for fallow periods to be optimal, it is possible that the average productivity of labor increases with agricultural intensification. This is particularly true if there is a discrete shift from a land extensive to a more intensive farming method. In addition, Boserup argued that a larger and denser population facilitates the development of economic and social infrastructures which improve agricultural productivity. Thus, it is possible to reconcile the greater labor requirement of intensive farming with an increase in the average productivity of labor.

BEST AVAILABLE

CONTINUOUS AND CYCLICAL FARMING STRATEGIES FOR SOIL MANAGEMENT FOR SUSTAINABLE AGRICULTURE

1. Introduction

The conservation of soil resources for sustainable agriculture is a concern of increasing importance in many parts of the world. In the semi-arid regions of Africa, low rainfall is a critical limiting factor for agricultural production and so farm productivity depends critically upon the soil depth and soil structure, particularly the ability of the soil to capture and retain the limited rainfall. Population growth has led to the clearing of forests to cultivate more land and to more intensive cultivation of the land, particularly through shorter fallow periods. As a result, the rate of soil erosion and the rate of deterioration of the soil quality have increased. Crop productivity has been impaired as the quality of the soil resource has declined because of the more intensive cultivation and the sustainability of agriculture is threatened. The economic nature of this problem can be characterized as a trade-off between current production and the future productivity of the soil resource.

Optimal control theory and dynamic programming models provide a useful framework of analysis for intertemporal economic problems; they have been applied to a wide variety of natural resources, including the management of soil resources. McConnell (1983) examines an optimal control model of soil conservation in which current output is a function of the state variable, soil depth, and the control variables, soil loss and an index of other farm inputs. Bhide, Pope, and Heady (1982) and Miranowski (1984) use dynamic optimization models to examine soil erosion in Iowa and Segarra and Taylor (1987) examine the optimal cropping rotation in south-central Virginia. Burt (1981) includes two state variables, soil depth and the percent of organic matter in the top 15 centimeters of soil in a model which examines soil

erosion and the optimal crop rotation in the Palouse region of Idaho and Washington. Clark and Furtan (1987) also include two state variables, soil nitrogen and water, in a study of soil conservation and depletion in Saskatchewan.

Previous treatments of soil conservation in the literature have focused on optimal rates of soil depletion when the net benefit function is strictly concave. With the assumption of a concave net benefit function and an infinite planning horizon, the optimal path is either to approach a steady-state equilibrium asymptotically or to exhaust the soil resource in finite time. Whether or not soil exhaustion is optimal depends upon the rate of return to the soil resource relative to the rate of discount. The optimal steady-state level for the soil resource occurs where the own rate of return to the soil resource (the sum of the value of the marginal productivity of the soil in the production of crops and the value of its marginal productivity in the regeneration of the soil resource) is equal to the rate of discount. It is optimal to exhaust the soil resource if its own rate of return is less than the rate of discount at all levels of the soil resource.

However, if there is a nonconvexity in the net benefit function for farming, then continuous farming in a steady-state equilibrium may not be the optimal farming strategy. Lewis and Schmalensee (1975, 1977, 1979) demonstrate that if there is a nonconvexity to the net benefit from the harvest of a renewable resource, then the optimal management of the resource can involve cycles of exploitation and regeneration. The Lewis and Schmalensee model applies to any renewable resource with a concave regeneration function although their discussion centers exclusively on fisheries.

This paper examines an optimal control model of soil management which allows for nonconvexities in the net benefit function. This can be particularly relevant to the problem of soil management in marginal semi-arid farmlands. The next section of the paper presents a

standard one-state variable model in which farm productivity is a function of soil depth and farming intensity. Section 3 discusses the optimal continuous farming strategy and section 4 follows Lewis and Schmalensee (1975, 1977, 1979) to demonstrate that with nonconvexities in the net benefit function, it may be that neither a continuous farming strategy nor exhaustion is the optimal soil management strategy. Instead, the land should be used in cycles of exploitation and regeneration. The implications of the results for agricultural development and sustainable agriculture are discussed in section 5.

The results tend to be somewhat intuitive and yet they direct our thinking about soil management practices in a way that is not usually discussed. In addition, the model highlights some of the rationale for shifting agriculture and points to important issues which must be addressed in a discussion of sustainable agriculture. In particular, it points to the complexity of the economic dynamics of soil management and the importance of key biological and economic relationships.

The results are important to the discussion of appropriate farming strategies for developing countries. Shifting agriculture and long fallow systems have been criticized for their low productivity per hectare and the inability to increase the productivity of land and labor with these farming systems (for example, Ruthenberg, 1980, pp. 59-60). Development efforts have been geared to developing more "...stable, permanent and productive agriculture in place of the centuries-old shifting cultivation and related bush fallow systems (ter Kuile, 1985, p. 15)." Indeed, in some cases, shifting agriculture and long fallow systems are criticized as being wasteful.[1] On the other hand, it also is commonly recognized that there are economic impediments to more intensive, continuous farming strategies. In particular, labor requirements,

particularly at planting time, are an important constraint on the adoption of more permanent farming practices (e.g., Ruthenberg, 1980, p. 52, and Delgado and McIntire, 1982).

The model presented here suggests that cycles of exploitation and regeneration, as represented by shifting agriculture and long fallow systems, can be the optimal economic method for managing soil fertility and achieving sustainable agriculture. It is even possible that in some cases, it is the only economically viable means of sustaining agricultural productivity. The model is also relevant to other land uses including the more familiar use of short fallow periods to conserve soil moisture, the use of crop rotations to manage other soil characteristics, and crop rotations for pest management.

2. The Soil Resource Model

Consider a one state-variable model of soil management in which the net benefit from farming the land at time t, denoted by $B(X,s)$, is a function of the state of the soil resource at time t, denoted by $X(t)$, and the depletion of the soil resource at time t, denoted by $s(t)$. This general specification of the soil resource can be used to examine the optimal conservation of different soil characteristics. The state of the soil resource could be the moisture content of the soil (e.g., Young, 1986), the depth of the soil (Burt, 1981, and McConnell, 1983), the nitrogen content of the soil (Clark and Furtan, 1983), organic matter (Burt, 1981), or a combination or index of relevant soil characteristics which describe the fertility of the soil. Limiting the model to one state variable greatly simplifies the theoretical analysis without changing the basic qualitative nature of the results.[2]

The net benefit from farming also depends upon the rate of depletion of the soil resource. The crop yield depends upon the 'farming intensity' which can represent a schedule of various 'activities'—crop selection, tillage, etc.—which affect the yield from the current state of the

soil resource and also affect the depletion of the soil. That is, an alternative formulation of the model could specify farming intensity, say $u(t)$ as the control variable and the depletion of the soil resource would be a function of the level of farming intensity, $s(t) = f(u(t))$.

In the present formulation, the relationship between farming intensity and soil depletion is embedded within the net benefit function. This formulation simplifies the exposition of the cyclical farm strategies. The formulations are the same when there is a monotonic relationship between farming intensity and soil loss.[3] It is assumed that $B_X > 0$, $B_s > 0$, $B_{XX} < 0$, $B_{ss} < 0$, $B_{Xs} \geq 0$. If $B_{Xs} > 0$, then the marginal return to a given level of soil depletion (farming intensity) increases with the state of the soil resource (e.g. soil depth or soil moisture).

Since farming depletes soil fertility, it affects agricultural production in future periods. The future productivity of the soil also depends upon the natural regeneration of the soil, denoted by $g(X)$. In most of the previous dynamic models of soil erosion, it has been assumed that the soil regenerates at a constant rate k (for example, McConnell, 1983). However, it is possible, and perhaps more likely, that the regeneration of the soil could depend upon its current state.

For example, the regeneration of the soil resource can depend upon the deposition of residue organic matter in previous years which, in turn, depends upon the state of the soil resource. In some cases, the regeneration of soil productivity actually occurs when the fallow vegetation is burned and the nutrients in the vegetation are released into the soil. Consequently, the natural rate of regeneration of the soil can be low when the state of the resource is low and then increase, reach a peak, and then decline as the state of the soil increases. This also allows for irreversible degradation of the soil such as occurs with desertification, and it allows for a maximum level of soil productivity. In the case of soil moisture, the carry-over of seasonal

rainfall from a year of fallow can depend upon the soil moisture content of the soil and there can be an upper limit to soil moisture.

For this general specification of soil regeneration, then, it is assumed that there exists a maximum state of the soil resource $\tilde{X}$ such that $g(\tilde{X}) = 0$. It also is possible that there is a state of the soil resource below which the soil does not regenerate. This state is denoted by $\underline{X}$ so $g(\underline{X}) = 0$. It also is assumed that $g(X)$ is concave for $X \geq 0$ (there can be a discontinuity at $X = 0$). Then the equation of motion is given by: $\dot{X} = g(X) - s$. Both the more general specification and the special case $g(X) = k$ are examined here and they are depicted in Figures 1a and 1b. It also is assumed that $X(0) > \underline{X}$ and that there exists an $s(0)$ such that $B(X(0), s(0)) > 0$ (this implies that farming is desirable at some time).

The net benefit function and the equation of motion capture the notion that farming the soil entails a trade-off between current returns and the future productivity of the soil. That is, more intensive farming increases the rate of depletion of the soil resource and increases the current net return but reduces the future productivity of the soil.[4]

3. Continuous Farming Strategy

The farmer selects the time path for soil depletion which maximizes the present value of net returns from the land over a given time horizon. Formally, the problem is to choose the time path for soil depletion, $s(t)$, which maximizes:

$$\int_0^T e^{-\delta t} B(X(t), s(t))\, dt + e^{-\delta T} V(X(T)) \tag{1}$$

subject to:

$$\dot{X}(t) = g(X(t)) - s(t) \tag{2}$$

$$s(t), X(t) \geq 0 \quad \forall\ t; \tag{3}$$

where T denotes the length of the planning horizon (which could be endogenous or exogenous, finite or infinite), $V(X(T))$ denotes the value of the state of the soil resource at the terminal time, and δ denotes the rate of discount.

The current-value Hamiltonian is given by:

$$H(X, s, \lambda) = B(X(t), s(t)) + \lambda(g(X(t)) - s(t)) + \alpha_1 s(t) + \alpha_2 X(t) \tag{4}$$

where $\lambda(t)$ is the costate variable for the equation of motion governing soil depth and represents the current value shadow price, or marginal value, of the soil resource and the α_i's are the Lagrange multipliers associated with the non-negativity constraints.

The first order conditions for an interior solution are:

$$\partial H/\partial s = B_s(X, s) - \lambda = 0 \tag{5}$$

$$\dot{\lambda} = \delta\lambda - \partial H/\partial X = \delta\lambda - B_X(X, s) - \lambda g'(X) \tag{6}$$

Equation (5) is the static efficiency condition that the marginal net benefit from soil depletion is equal to the marginal cost of soil depletion (where the latter is the value of soil resource times the marginal soil loss). Equation (6) is the dynamic efficiency condition which insures that the rate of return to the soil asset is equal to the rate of discount and, therefore, to the rate of return to other assets in the economy. The rate of return to the soil asset is the capital gain on its value, $\dot{\lambda}/\lambda$, plus the marginal productivity of the soil in farming, B_X/λ, plus the marginal productivity of the state of the soil resource in the regeneration of soil resource, $g'(X)$.[5] If natural rate of soil regeneration is constant, then $g(X) = k$, and the last term of the return to the soil asset is zero.

If $g(X) = k$, then the dynamic efficiency condition, equation (6), can be integrated with respect to time to yield:[6]

$$\lambda(t) = \lambda(T)e^{-\delta(T-t)} + \int_t^T e^{-\delta(\tau-t)} B_X(X(\tau), s(\tau))\, d\tau. \tag{7}$$

The current value shadow price for soil depth can be separated into two parts. The first term on the right hand side is the current value, at time t, of the scarcity rent associated with the soil resource. The second term can be viewed as a 'degradation charge' which represents the discounted value of the cost imposed on the future because the current soil loss increases the marginal cost, in terms of reduced productivity, of any future soil losses. Both the scarcity rent and the degradation charge must be covered by the marginal net benefit from farming.

Differentiating the static efficiency condition, equation (5), with respect to time, and using the dynamic efficiency condition, equation (6), yields the time derivative of the control path for soil depletion:

$$\dot{s}(t) = \frac{(\delta - g'(X))\lambda - B_X - B_{Xs}(g(X) - s)}{B_{ss}} \tag{8}$$

The denominator of equation (8) is negative. The numerator is positive when λ is increasing and the soil resource is decreasing. In this case, then, soil depletion is decreasing over time.

Equation (5) implicitly defines the optimal soil depletion, $s(t)$, as a function of the state of the soil resource, $X(t)$, and its shadow price, $\lambda(t)$. Consequently, at any point in time, the entire system is described by the state of the soil and its shadow price at that time. Indeed, the optimal trajectories can be characterized by the differential equations:

$$\dot{X} = M(X, \lambda) = g(X) - s(X, \lambda) \tag{9}$$

$$\dot{\lambda} = N(X, \lambda) = \lambda[\delta - g'(X)] - B_X(X, s(X, \lambda)) \tag{10}$$

The optimal path $s^*(t)$ satisfies equations (9) and (10), the initial condition $X(0) = X_0$, the non-negativity conditions, and the transversality condition(s). Thus, the optimal solution $s^*(t)$

is a function of the initial soil depth, the time horizon, the rate of discount, and the parameters and functional forms of the net benefit and soil loss equations.

The qualitative nature of the optimal time path for soil depletion, and therefore soil loss, can depend critically upon the time horizon. The transversality, or boundary, conditions are:

$$\lim_{t\to T} X(t) \geq 0, \quad \lim_{t\to T} e^{-\delta t}\lambda(t) \geq 0, \quad \text{and} \quad \lim_{t\to T} e^{-\delta t}\lambda(t)X(t) = 0. \tag{11}$$

if T is given and $X(T)$ is free,[7] and:

$$\lim_{t\to T} e^{-\delta t}[B(X(t), s(t)) + \lambda[g(X(t)) - s(t)]] + e^{-\delta t}V(X(t)) = 0 \tag{12}$$

if the time horizon is endogenous. If the time horizon is finite, then the time path for the exploitation of the soil depends upon the length of the time horizon and the terminal value of the soil resource. With a finite time horizon, there must be, at least implicitly, a valuation for the terminal level of soil depth, $V(X(T))$. This terminal valuation essentially represents a summary statement of all the economic and technological conditions which are expected to prevail after the terminal time. Equation (11) requires that if the terminal state of the soil resource is positive, then the terminal shadow price of the soil resource is equal to the marginal value of the soil resource at the end of the planning horizon. If the terminal value of the soil is zero, then this implies that either the resource is exhausted at the end of the time horizon or the scarcity rent for the soil resource is zero. The assumption of a finite time horizon and low terminal value can force the optimal level for farming intensity to increase over time whereas an infinite planning horizon would yield a monotonically decreasing time path for farming intensity and soil loss (McConnell, 1983; Bhide, Pope, and Heady, 1982).

Sustainable agriculture suggests an infinite (or at least indefinite) planning horizon. In this case, the optimal path can be to go to a steady-state equilibrium. A steady-state is defined

by $\dot{\lambda} = \dot{X} = 0$, which implies $\bar{s} = g(\bar{X})$, and $\delta = g'(X) + B_X(X,s)/\lambda$, where $\bar{X}$ and $\bar{s}$ denote the steady state of the soil resource and the steady state soil depletion, respectively. Static efficiency requires $\lambda = B_s(X,s)$. Therefore, the steady state of the soil resource, $\bar{X}$, is defined by the condition:

$$\frac{B_X(\bar{X}, g(\bar{X}))}{B_s(\bar{X}, g(\bar{X}))} + g'(\bar{X}) = \delta \tag{13}$$

A sufficient condition for the existence of a steady-state equilibrium is $g'(0) > \delta$.

The phase diagram in the λ, X space is depicted in Figure 2, both for the general case of a concave soil regeneration function and the special case of constant soil regeneration.[8] The $\dot{X} = 0$ curve represents combinations of the state of the soil resource and its price where the intensity of farming is just equal to the natural regeneration of the soil and it can be interpreted as the steady state supply function for the soil resource (Smith, 1977). The general specification for the natural regeneration function makes it possible for this 'supply curve' to have a downward sloping segment. The $\dot{\lambda} = 0$ curve represents combinations of the state of the soil resource and its shadow price for which the own rate of return to the soil asset is just equal to the rate of discount and it can be interpreted as the steady state demand for the soil resource (Smith, 1977).

If a steady-state equilibrium exists, then the state of the soil resource is monotonically decreasing and the shadow price of soil is monotonically increasing along the optimal path when the initial state of the soil resource is greater than the steady-state level. The movement of the state and costate variables is reversed if the initial soil resource is less than the steady-state level.[9] If the net benefit function, $B(X,s)$, is strictly concave everywhere, then the optimal strategy is either to exhaust the soil resource or to move to the steady-state equilibrium depending upon the own rate of return of the resource relative to the rate of discount. The

introduction of a concave soil regeneration function and the productivity of the soil resource make it possible for multiple steady-state equilibria to occur. If a steady-state equilibrium is unique, then it is a saddle point equilibrium and the equilibrium is stable.[10]

Total differentiation of equation (13) yields:

$$\frac{d\bar{X}}{d\delta} = \frac{-B_s}{(\delta - g')[B_{ss}g' + B_{Xs}] - g'B_{Xs} - B_{XX} - B_s g''} < 0 \tag{14}$$

if $\bar{X}$ is a stable equilibrium. In the special case $g(X) = k$, this reduces to:

$$\frac{\partial \bar{X}}{\partial \delta} = \frac{B_s}{B_{XX} - \delta B_{Xs}} < 0. \tag{15}$$

If the discount rate increases, the $\dot{X} = 0$ curve shifts downward as the steady state demand for the soil resource decreases. Consequently, the steady state of the soil resource decreases and the equilibrium shadow price decreases in response to the higher rate of discount. The lower shadow price results in an increase in the rate of soil depletion at each state of the soil resource and a higher rate of time preference results in a lower quality soil resource in the steady-state. Indeed, there is a rate of time preference which is great enough for it to be optimal to exhaust the soil resource.

In the special case of constant soil regeneration, the value of k also affects the steady state of the soil resource:

$$\frac{\partial \bar{X}}{\partial k} = \frac{B_{Xs} - \delta B_{ss}}{(\delta B_{Xs} - B_{XX})} > 0. \tag{16}$$

If the soil regeneration parameter k increases, the $\dot{X} = 0$ curve shifts downward. That is, the steady state supply curve shifts out, the steady state shadow price of the soil resource decreases and the steady state of the soil resource increases. The rate of soil depletion is greater at each state of the soil resource. The opposite effects occur in the case of a decrease in the rate of soil regeneration.

This section of the paper assumed that the net benefit function was concave in the control variable, soil depletion. If there are non-convexities in the net benefit function, then it can be optimal to farm the land in periodic cycles of exploitation and regeneration (Lewis and Schmalensee, 1975, 1977, 1979).[11] This could occur, for example, if there are fixed costs which do not vary with the level of farming but are not incurred if the land is fallow, if there is increasing marginal productivity over some range of farming intensity, or if there is a discontinuity in the soil loss equation when farming occurs. The longer cycle bush-fallow pattern of cultivation and crop-fallow rotations for managing soil moisture in semi-arid lands represent this type of farming strategy.

4. Nonconvexities and Cyclical Farming Strategies

If there is a nonconvexity in the net benefit function, then a continuous farming strategy leading to a steady-state equilibrium may be only a local maximum. That is, there can be a non-continuous farming strategy which yields a higher present value from the soil resource.

A nonconvexity is introduced into the net benefit function if there are fixed costs to farming which are not incurred if the land is not farmed. In this case, the net benefit is zero if the land is not farmed and $B(X,s) - F$ if the land is farmed, where F denotes the fixed cost of farming, and there is a discontinuity in the net benefit function at $s = 0$. If the productivity of the soil declines sufficiently as the state of the soil resource declines, then net benefits may be negative at all levels of farming intensity (soil depletion)—see Figure 3. In this case, the farmer is clearly better off by avoiding the fixed cost of farming by not planting a crop and letting the productivity of the soil regenerate before planting a crop in a later year (or perhaps abandoning the land if the cost of returning to farm the land is too great).

If there is a return to the land in the absence of farming which is not received when the land is farmed, then the opportunity cost of farming includes the forgone return to unfarmed land and represents a type of fixed cost to farming. Consequently, the opportunity cost of fuelwood and forage which can be provided if the land is in forest or bush fallow can be viewed as a fixed cost of farming the land.

Nonconvexities in the net benefit function can occur in other ways as well. For example, there can be a nonconvexity in crop yields at low levels of farming intensity (and therefore soil depletion). This could arise because because of a minimum level of the soil resource required for a positive yield or because the marginal productivity of the soil is increasing over some range of the level of farming intensity.

A nonconvexity in the Hamiltonian, rather than the net benefit function, occurs if there is a minimum level of soil loss, denoted σ, when the land is farmed. That is, if $s(t) \geq \sigma > 0$ when the land is farmed at any level of cultivation but $s(t) = 0$ when the land is fallow, then there is a nonconvexity in the Hamiltonian. The effect of this jump in the soil loss function is similar to the effect of a fixed cost of production. The only real difference is that in this case, the fixed cost of farming, $\lambda\sigma$, is endogenous since λ is endogenous. If λ was constant, then the effect would be identical to a constant fixed cost to farming. Since λ increases (decreases) as the state of the soil resource decreases (increases), the effect is to have this 'fixed cost' of farming increasing over the farming cycle, which would contribute to a shorter farming cycle.

In the presence of nonconvexities, the optimal soil management strategy can be to farm the land in cycles of exploitation and regeneration. Indeed, there are conditions which are sufficient to insure that a cyclical farming strategy is optimal. The most straightforward case is when there is a fixed cost to farming. The discussion here follows that of Lewis and Schmalensee

(1975, 1977, 1979). The fixed cost model can be viewed as a first approximation to the other nonconvexities.

It is clear that there is a fixed cost which is large enough for it to be optimal to not plant a crop. For a given fixed cost, let $\hat{X}$ denote the largest X for which $B(X, s(X, 0)) \leq F$. That is, $\hat{X}$ is the greatest lower bound for the state of the soil resource for which it is possible to have non-negative net benefits, including the fixed cost. If the state of the soil resource falls below $\hat{X}$, then it must be better to not plant a crop. If this occurs, then the option is to abandon the land permanently or to return to farm the land at a later date when the soil resource has sufficiently regenerated to overcome the fixed cost of farming.[12] Whether or not permanent abandonment is optimal depends upon the cost of returning to farm the land, denoted by R.

If returning to the land to farm is not possible ($R = \infty$), then abandonment must be permanent. A unique abandonment strategy exists if the net benefit from farming at the steady-state of the continuous farming strategy, including the fixed cost, is negative ($B(\bar{X}, g(\bar{X})) \leq F$). A unique abandonment strategy also exists if the initial state of the soil resource is less than its optimal steady-state under continuous farming and net benefits are negative without further depletion of the soil resource ($X_0 < \bar{X}$ and $B(X_0, g(X_0)) \leq F$) (Lewis and Schmalensee, 1977, Proposition 6; Lewis and Schmalensee, 1975, Proposition 3.4). In either case, the productivity of the soil is not sufficient to overcome the fixed cost of farming unless the rate of soil depletion is greater than the rate of depletion which allows the state of the soil resource to be sustained.[13]

The most interesting case is when the cost of returning to farm the land is positive but finite ($0 < R < \infty$).[14] In this case, sufficient conditions for it to be optimal to farm the land in cycles of exploitation and regeneration are given by: (a) the net benefit (including the fixed cost) from farming at the steady-state of the continuous farming strategy is negative

$(B(\bar{X}, g(\bar{X})) \leq F \ \ \forall \ \bar{X})$; (b) there is a level of the soil resource greater than the minimum viable level for which the maximum net benefit from farming (including the fixed cost) is positive $(\hat{X} > \underline{X})$; and (c) there is a level for the soil resource where the present value of returning to farm the land is greater than the cost of returning to farm the land; that is, there exists an $X < \tilde{X}$ such that $V_a(X) > R$ where V_a denotes the discounted net benefit from an optimal abandonment strategy beginning at X (Lewis and Schmalensee, 1977, Proposition 11).

The economic intuition behind these sufficient conditions is straightforward. The fixed cost is such that the net return to farming is negative in the steady-state. Thus, a continuous farming strategy cannot be optimal since eventually the net return to farming is negative (condition a) and it is better not to farm the land. However, the (temporary) abandonment of the land occurs at a viable level of the soil resource (condition b). Consequently, the soil resource regenerates while it is fallow. However, the land is not permanently abandoned since eventually the soil resource reaches a level at which the present value of farming the land, even with the intent of abandonment, is greater than the cost of returning to farm the land. But since a continuous farming strategy is not optimal, eventually it again becomes better not to farm the land and the cycle repeats itself.

Lewis and Schmalensee (1979) point out that these conditions for the optimality of cyclical exploitation are stronger than necessary. Even if the net benefit, including the fixed cost, is positive in the steady-state, this may be only a local maximum. It could be better to farm the land in cycles of exploitation and regeneration if the present value of the increased productivity from the higher states of the soil resource is greater than the present value of the net benefits foregone while the soil resource is regenerating. This is because incurring the fixed cost of farming in each year could result in an annual return which is less than the average return from

a cycle of farming and fallow. In this case, the globally optimal strategy would have to be determined by a comparison of the present values for each farming strategy in the particular case.[15]

The optimal strategy is stationary if the soil regeneration and net benefit functions, the fixed cost to farming, the cost of returning to farm the land, and the rate of discount are independent of time. That is, the optimal soil depletion is the same whenever the same state of the soil resource is encountered. A farming cycle, then, is defined by the state of the soil resource at which farming is stopped, denoted by X^S, and the state of the soil resource at which farming resumes, denoted by X^R. The cycle interval is then defined to be $[X^S, X^R]$.

Increases in fixed costs reduce the optimal amount of time spent farming the land (Lewis and Schmalensee, 1979, Proposition 3).[16] This provides some insight into the effect of changes in price or cost on the optimal cycle interval. To some degree, an increase in price is similar to a decrease in fixed cost and so the land is exploited for longer periods when the price is higher. Essentially, the higher price reduces the interval of nonconvexity and makes it easier to overcome the higher fixed costs associated with a continuous farming strategy. However, the shift in the net benefit function is parallel for a change in fixed costs but not necessarily for a price change and so the analogy is not exact (see Figure 4). Similarly, a decrease in operating costs would shift the net benefit curve upward as would a decrease in fixed costs.

An increase in fixed cost increases the state of the soil resource at which farming is resumed (Lewis and Schmalensee, 1979, Proposition 5). Thus an increase in the price of farm output can induce the land to be farmed again at a lower state of the soil resource. Determinate conditions for the effect of a fixed cost on the state of the renewable resource for which it is optimal to temporarily stop farming could not be derived (Lewis and Schmalensee, 1979).

An increase in the cost of returning to farm the land, R, increases the state of the soil resource at which return occurs and decreases the state of the soil resource at which the land is abandoned. This increases the cycle interval and increases the time period between successive returns (Lewis and Schmalensee, 1975, Propositions 5.5 and 5.6).

5. Discussion

Whether a continuous or cyclical farming strategy is optimal depends upon the available agricultural technology, the geological and biological conditions governing soil regeneration, and the economic conditions in a specific location. In the presence of nonconvexities, long fallow periods can be the farming strategy which maximizes the present value of soil resource.

Population growth and expanding markets can affect the economic factors which determine the optimal farming strategy. Increasing population growth which increases the price of agricultural commodities relative to the cost of production will increase the net return to farming at any given level of the soil resource. This tends to reduce the importance of the nonconvexity associated with fixed costs to farming, the fixed cost of soil enhancement activities, or discontinuities in the regeneration of soil productivity when the land is farmed. In essence, the greater population makes it economical to bear the greater fixed costs associated with a continuous farming strategy.

This analysis provides some support to the Boserup (1965) argument that population growth is a precondition for the intensification of agriculture from forest fallow to bush fallow to short fallow to annual cropping. Boserup argued that more intensive agricultural techniques, in the sense of more continuous farming, were generally available before their adoption but were not used until population growth made them the appropriate technological choice. Population

growth and increasing market opportunities make it profitable to bear the greater fixed costs associated with a continuous farming strategy.[17]

A variety of factors which affect the viability of continuous farming strategies must be considered if such strategies are to be successfully adopted. It cannot be assumed that fallow lands necessarily imply a land surplus; it may simply be that the fallow is the most efficient means of regenerating soil productivity. Policies which keep the price of agricultural outputs artificially low or which increase the price of agricultural inputs can impede the adoption of continuous farming strategies. Unfortunately, such policies are not uncommon. Agriculture production in developed countries is often protected through subsidies or other trade policies and this holds down the world price for the protected commodities. On the other hand, agricultural production in developing countries is often penalized through overvalued exchange rates and pricing policies intended to keep urban food prices low. Low input prices are also important since output prices must rise relative to input prices in order to reduce the importance of the nonconvexities associated with farming. Growing population without increased food prices and decreased input costs can push the farming strategy from cycles of exploitation and regeneration to a strategy of exhaustion and abandonment of the soil resource.

Price and cost considerations are also important for the successful introduction of a new farming technology which could cause a shift from a cyclical to a continuous farming strategy. An example would be the use of tied ridges in sub-Saharan Africa. Tied ridges enhance the collection of rainfall and improve both the yield from farming and reduce the level of soil erosion (Matlon and Spencer, 1984; Butcher and Day, 1987). The disadvantage to tied ridges is the amount of labor or capital required to build the ridges. The labor requirement is 100 hours per hectare with draft animals and 150 hours without animals (Butcher and Day, 1987).

Furthermore, animals are relatively expensive and require a good deal of land for forage. The timing of the labor problem is also important as planting needs to be done quickly with the onset of rain (Ruthenberg, 1980). With tied ridges, there also is greater risk of crop failure with the absence of rain in the early season since the crop is planted in the ridges and the plants are more susceptible to failure without rain until the roots are firmly established.

The successful adoption of continuous farming strategies also can require changes in land tenure systems. If population density is low, then extensive systems of agriculture which employ long fallow periods can be the optimal farming strategy. In the case of long fallow periods, it is not as important for an individual farmer to maintain secure tenure rights to a particular piece of land over a long period of time since no individual investment in the land is made. Of course, there must be secure tribal tenure rights in order to keep the cost of returning to the land low enough so that abandonment is not the optimal strategy. However, a continuous farming strategy requires secure tenure in the land particularly when the preservation of soil fertility requires private investment in the soil resource. Without secure property rights in the regenerated productivity of the soil, the farmer's incentive to manage the land as an investment in future soil productivity is greatly diminished.

There are a number of important complications which have not been incorporated into the model presented here. For example, many of the physical and economic relationships are stochastic in nature and risk analysis is an important topic for further research. First, there is an intratemporal risk associated with the net return to farming within a given year which may affect the optimal strategy of farmers who need a reasonable assurance of obtaining a subsistence level of output. Second, there is an intertemporal risk associated with the uncertainty about the future productivity of the soil resource, including the possibility of exploiting the land beyond

the point at which regeneration is possible. That is, there can be a danger of falling below a 'safe minimum standard.'[18]

From a social viewpoint, the external costs and benefits of different farming strategies also must be considered.[19] Forest and bush fallow may have beneficial externalities if continuous coverage of the soil helps to prevent desertification. On the other hand, fallow could also have detrimental environmental effects as in the case of fallow for soil moisture (Young, 1986). Or there could be adverse environmental effects of the re-entry into farming after a period of regeneration. There is not complete agreement on the environmental costs of shifting agriculture. As Sanford (1985, p. 45) notes, "Ecology...tends to emphasize maintenance of soil fertility through constant vegetation cover and rotation for sustained yield. The result is that ecologists in general would like to see an increase in shifting cultivation, albeit in a modified form, while in the agriculture faculties many would urge its abolition."

The model presented here implicitly assumed that the net benefit function is stationary. In general, the net benefit function can be changing over time due to changes in input and output prices and technological changes in the agricultural production function. The models can be extended to examine how the conservation of the soil resource and the optimal farming strategy is affected by changing price patterns and technological progress.

6. Summary

The optimal management of a soil resource depends upon a variety of factors including the marginal productivity of the soil resource, the value of the agriculture production, the cost of agricultural inputs, the rate at which the soil resource regenerates, the rate of discount, the planning horizon, and the value of the soil resource at the end of the planning horizon. Of

particular interest from a broad social perspective is the management of the soil resource so that agricultural production can be sustained over a long-term planning horizon.

In principle, it can possible to sustain agricultural production either through a steady-state continuous farming strategy or through a farming strategy with cycles of exploitation and regeneration. Determination of the optimal strategy requires a careful analysis of whether or not the natural regeneration of the soil is great enough so that there exists a steady state equilibrium where the present value of the net return to continuous farming is positive and greater than the present value of the net return to a cyclical farming strategy. The key empirical relationships which must be determined include the natural regeneration of the soil at different states of the soil resource, including the state of the soil resource at which regeneration effectively becomes zero, and the net benefit from farming and soil conservation practices at different states of the soil resource.

Notes

[1]For example, Enabor (1985, p. 131) states, "Shifting cultivation...implicitly assumes that land is unlimited in supply. This assumption which is approximately valid only when population/land ratios are small,...encourages wasteful use of land by shifting cultivators." Kamajou (1985, p. 171) notes that, "Shifting cultivation may be satisfactory in some circumstances for subsistence, but it does not provide a sufficient technological basis for development. It also wastes land and forests."

[2]Of course, the construction of such an index is not trivial. A model with two state variables—soil depth and soil quality—is presented in Krautkraemer (1988). More complicated dynamic behavior occurs with two state variables, including the possibility of cyclical behavior in the state variables even in the absence of nonconvexities.

[3]McConnell (1983) also uses soil loss as the control variable. In McConnell's model, the relationship between farming intensity and soil loss is subsumed within the production function. Krautkraemer (1987) develops the current model with farming intensity as the control variable.

[4]This implicitly assumes that the schedule of farming activities is monotonic. That is, if $s = f(u)$, then $f'(u) > 0$ so that $\partial B/\partial u > 0$. There are farming activities which can enhance the soil resource at some cost. Since these activities reduce net benefits and soil depletion, they would represent less intensive farming methods in this context although this may not be the usual terminology for such activities. If there are fixed costs associated with these soil enhancement activities, they introduce nonconvexities which are important to the discussion of the cyclical farming strategy in section 4 below. A farming technique which reduces soil loss and increases the net return to farming would represent a technological innovation.

[5]The corner solution which occurs if $B_s(X, 0) > 0$ has been ruled out by the assumption that there is an $s(0)$ such that $B_s(X(0), s(0)) > 0$. If this was not the case, then it is optimal to never farm the land. This case has obvious differences with the case of abandonment discussed in section 4 below.

[6]With the more general specification of the soil regeneration function, an additional term, $\int_t^T \lambda(\tau) g'(X) e^{-\delta(\tau - t)} d\tau$, is added to the right hand side of equation (7) and the evolution of $\lambda(t)$ cannot be determined independently of the rest of the system. This additional term captures the value of the soil's marginal productivity in soil regeneration.

[7]A separate argument can be made to show that this condition also must hold when the time horizon is infinite.

[8]The derivations for the phase diagrams are standard and are not presented.

[9]If the net benefit function is linear in the rate of soil depletion, then the approach to the steady-state is a 'most rapid approach path' (Kamien and Schwartz, 1981). In this case, if the soil resource is below its steady-state level, then it is optimal to not farm the land until the soil depth has reached the steady-state level. If the state of the soil resource is better than its steady-state level, then it is optimal to farm the land at an exogenously given maximum level of intensity until the steady-state of the soil resource is reached.

[10]If there are multiple steady-state equilibria, then they will alternate between stable and unstable equilibria. The initial state of the soil resource then determines the optimal steady-state. It is possible that exhaustion is optimal for some initial values of the state of the soil resource while movement toward a steady-state with a positive soil resource is optimal from other initial values for the state of the soil resource (Lewis and Schmalensee, 1977; Cropper, 1988).

[11]Lewis and Schmalensee (1979) note other papers in the fisheries literature in which non-convexities generate optimal fishing cycles, including Jacquette (1972), Reed (1974), and Hannesson (1975).

[12]If the land is abandoned, then the terminal state of the soil resource, $X(T)$, should be $\hat{X}$. If $X > \hat{X}$, then net benefits from farming are positive and it is not optimal to abandon; if $X < \hat{X}$, then it would have been better to abandon earlier. If $\hat{X} < \underline{X}$, then abandonment implies exhaustion (Lewis and Schmalensee, 1977).

[13]Note that this includes the case in which the cost of soil conservation measures are too great relative to the return to farming, particularly if there are fixed costs associated with these activities.

[14]In a continuous time framework, if returning to farm the land is costless ($R = 0$), then the nonconvexity essentially disappears. This is because abandonment and return can take place infinitely often in a finite period of time (Lewis and Schamalensee, 1975).

[15]Lewis and Schmalensee (1975) refers to Lewis (1975) as a source for a computational algorithm. The practice of fallow to accumulate soil moisture can represent the case where the gains from accumulating soil moisture outweigh the foregone return from farming during the fallow year. Clark and Furtan (1983) present an empirical example where a year of fallow in a crop rotation gives a greater present value than continuous farming.

[16]As in Lewis and Schmalensee, the discussion here assumes there is a unique cycle interval.

[17]Thus, the Boserup argument of population determining the choice of technology runs counter to a Malthusian model in which population is limited by the agricultural technology.

[18]In the case of yellowfin tuna, Lewis (1981) found that uncertainty must be explicity considered in order to avoid a high possibility of large reductions in the stock of fish.

[19]Shortle and Miranowski (1987) compare private and social delpeletion paths of a continuous farming strategy when there are offsite costs to soil erosion.

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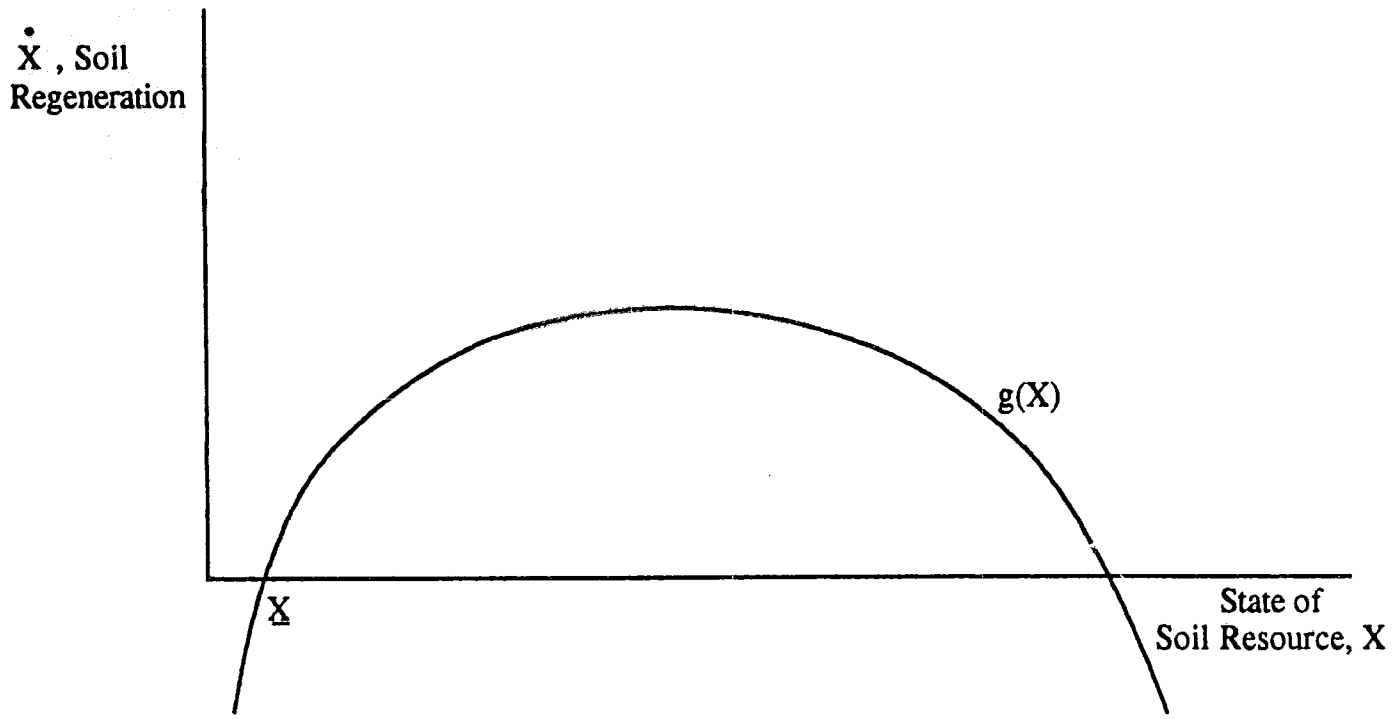

Figure 1a: General Soil Regeneration Function

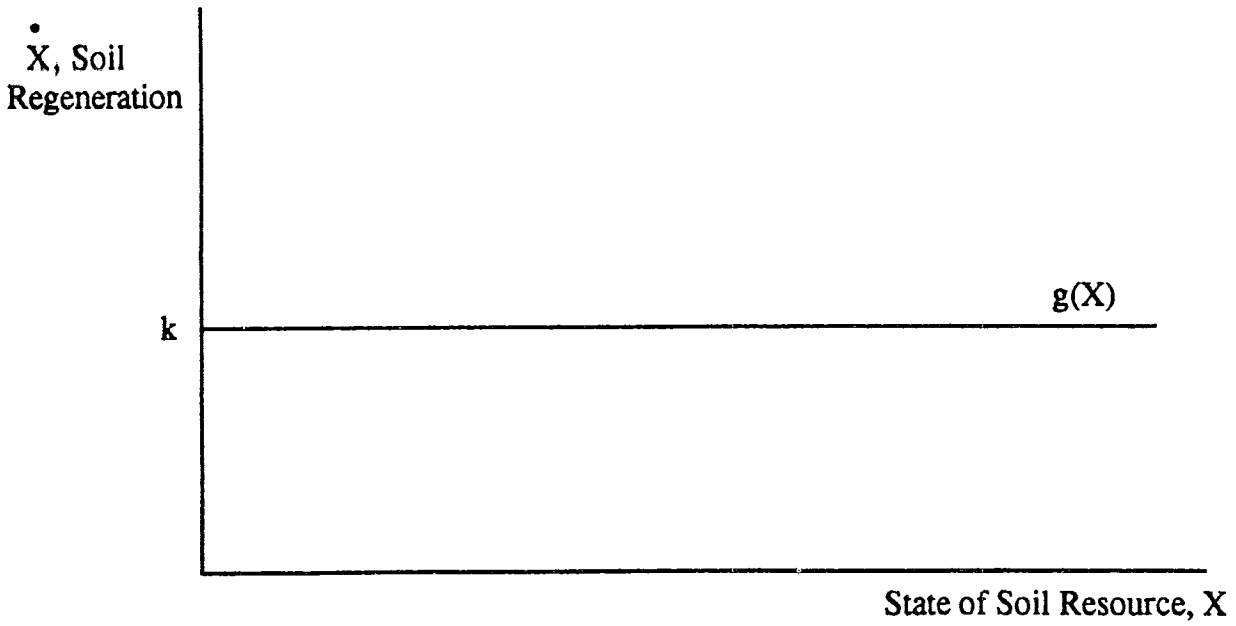

Figure 1b: Constant Soil Regeneration Function

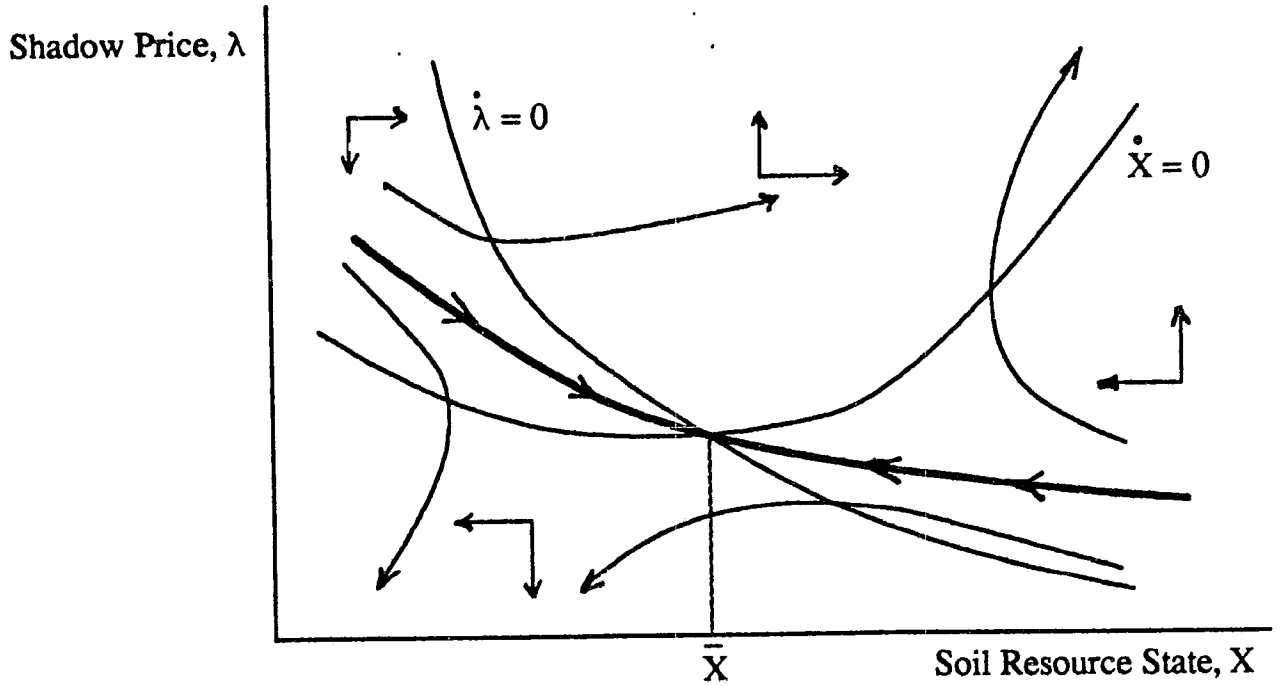

Figure 2a: λ , X Phase Diagram for the General Regeneration Function

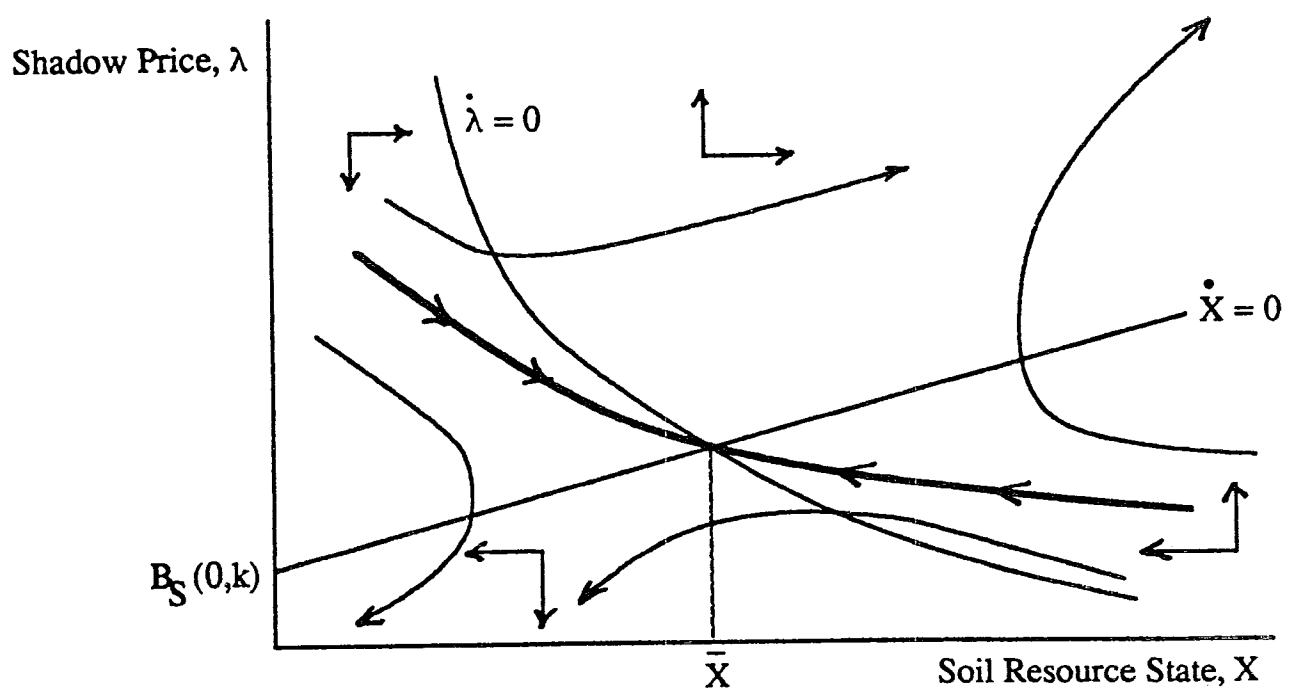

Figure 2b: λ, X Phase Diagram for the Special Case g(X) = k

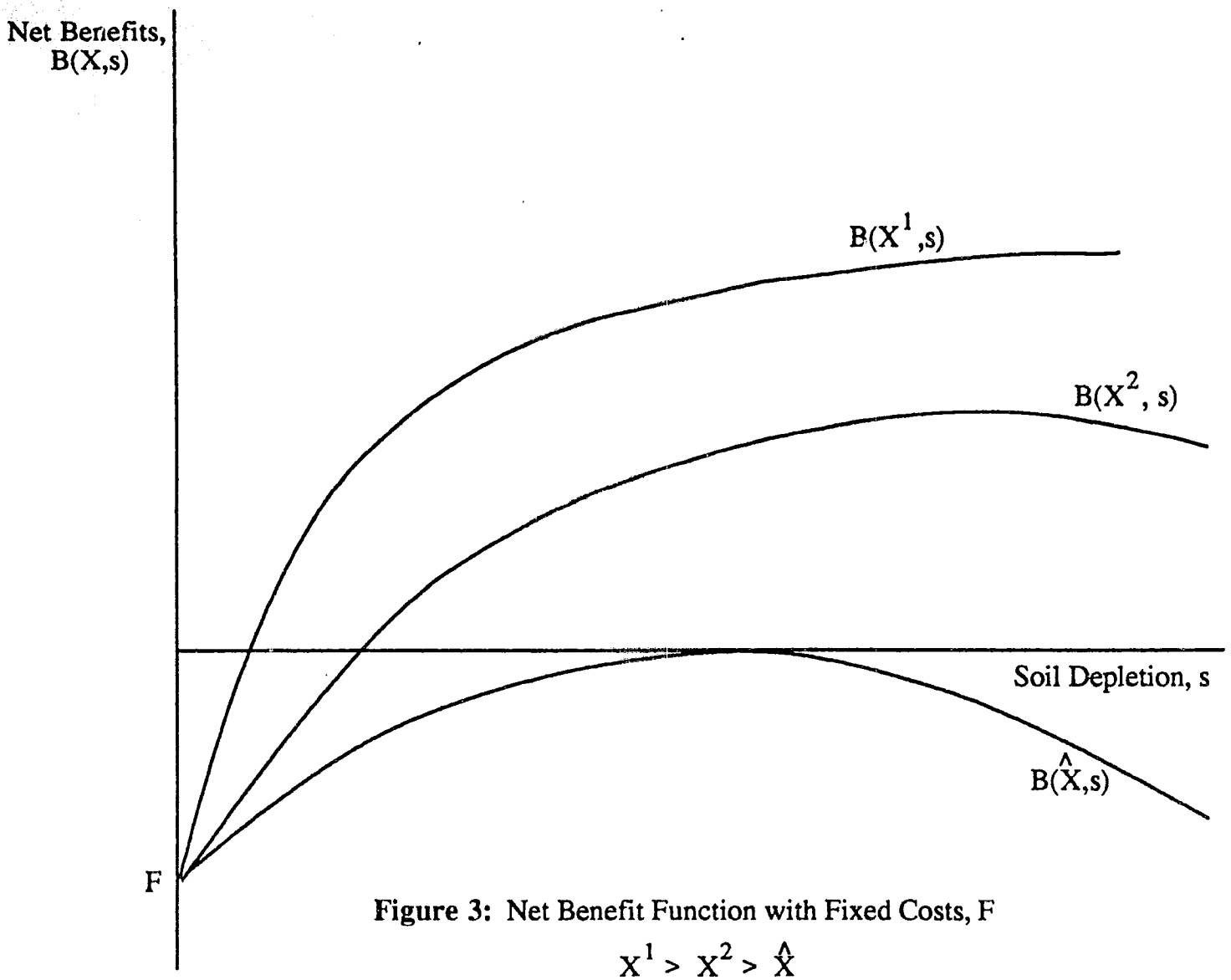

Figure 3: Net Benefit Function with Fixed Costs, F

$X^1 > X^2 > \hat{X}$

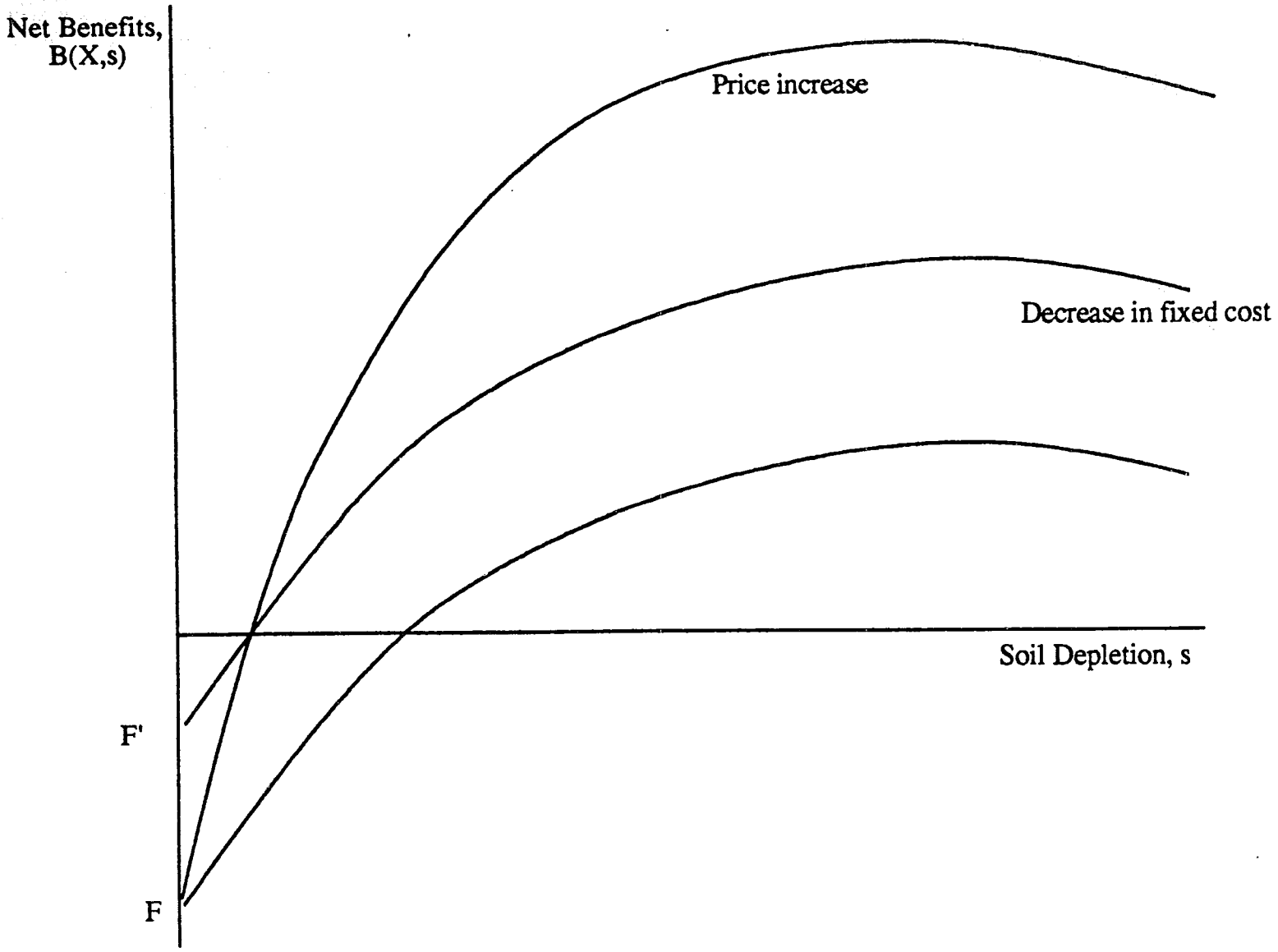

Figure 4: Effect of price increases and decrease in fixed costs on net benefit function.

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