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# CONTINUOUS AND CYCLICAL FARMING STRATEGIES FOR SOIL MANAGEMENT FOR SUSTAINABLE AGRICULTURE

by

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## Abstract

This paper considers continuous and cyclical farming strategies for the management of soil resources for sustainable agriculture. The results of the Lewis and Schmalensee (1975, 1977, 1979) analysis of the optimal use of a renewable resource in the presence of nonconvexities is used to demonstrate that cycles of exploitation (farming) and regeneration (bush fallow) can be the optimal strategy for soil management for sustainable agriculture.

# POPULATION GROWTH, SOIL FERTILITY, NONCONVEXITIES, AND AGRICULTURAL INTENSIFICATION

## 1. Introduction

In the classical model of agriculture and population, an increase in population is the result of an increase in agricultural productivity. Technological improvements in agriculture create an agricultural surplus which leads to an increase in the wage rate for agricultural workers. The higher wage rate induces an increase in population. Since there are diminishing returns at both the extensive and intensive margins of agricultural production, eventually the growth in population forces the wage rate to return to the subsistence level. This view of agricultural production presents a fairly pessimistic view of the prospects for economic growth and development. Technological progress is necessary to improve productivity but since population increases in response to higher wages, the wage rate always tends toward the subsistence level.

Ester Boserup (1965, 1981) presents a view of agricultural development and population growth in which the Malthusian relationship between agricultural production and population is reversed. Population growth, which is more or less exogenous, leads to more intensive use of agricultural land in the sense that a given piece of land is cropped more frequently. That is, the cropping pattern changes from long periods of fallow to shorter fallow to continuous cropping as the population grows. Population growth is seen as a precondition for agricultural development since even though the more land intensive techniques of farming are available, a higher density population is required for their adoption to be economically desirable.[1] A more concentrated and sedentary population facilitates the development of economic and social infrastructures which are favorable to agricultural productivity and are important for further economic development. Consequently, the Boserup perspective presents a more optimistic

view of population growth and agricultural development, particularly when the development of other sectors of the economy are considered.[2]

There are several formal models of the Boserup perspective on the relationship between population growth and agricultural development (Darity, 1980; Pryor and Maurer, 1982; Robinson and Schutjer, 1984; and Salehi-Isfahani, 1988).[3] The formal models assume a convex agricultural production technology and, in general, these models are not particularly optimistic about the prospects for agricultural development independent of technological progress in the agricultural sector. The theme that runs through these models is that population growth creates a demand for increased agricultural production which is supplied by more 'intensive' production—usually an increase in labor input (or 'effective' labor input) per unit of output. In the absence of an improvement in farming technology, either per capita consumption or leisure must fall. In either case, the population increase results in a decrease in well-being and the analysis has a Malthusian flavor.[4] In additon, and perhaps more importantly, none of these efforts have explicitly incorporated the role of soil fertility in the choice of farming technique and none have directly examined the transition from long fallow periods to continuous cropping.

The convexity of the production technology is an important reason why the prospects for agricultural development in response to population growth depend upon technological progress. That is, as more labor is applied to a fixed amount of land, the average productivity of labor must fall in response to the increase in population (even as the average productivity of land increases). In the absence of technological progress, living standards must fall—consumption and/or leisure must decrease in response to population growth.

This paper explicitly models the dynamics of soil fertility and demonstrates that nonconvexities are an important element of explaining the optimality of the use of long fallow periods

for soil management. Indeed, nonconvexities are necessary in order 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 it is optimal to follow a continuous farming strategy.

Since nonconvexities in the production technology are necessary in order for a cyclical farming strategy to be optimal, it is possible that the average productivity of labor increases as more intensive methods of farming are used, particularly when there is a discrete shift in the method of farming. Thus, it is possible to reconcile the greater labor requirement of intensive farming with an increase in the average productivity of labor. These observations are reinforced if there are nonconvexities, such as fixed costs, associated with the development of more intensive farming techniques, such as the fixed cost of irrigation systems or the cost of developing transportation or marketing infrastructures associated with the development of an urban industrial sector. This results in a more optimistic view of the prospects for agricultural development which is more consistent with the spririt of the Boserup analysis of agricultural development.[5]

The next section of the paper reviews the previous formalizations of the Boserup framework. Section 3 presents the dynamic model of soil fertility and section 4 examines the role of nonconvexities in explaining the use of long fallow periods. Section 5 discusses the relationship between population growth and agricultural intensification.

## 2. Agricultural Intensification

Boserup defines agricultural intensification in terms of the frequency with which a given hectare of land is cropped. Five types of land use are described, in order of increasing intensity:

forest-fallow cultivation, bush-fallow cultivation, short-fallow cultivation, annual cropping, and multi-cropping (Boserup, 1965, p. 15). The management of soil fertility is the key factor in determining the appropriate degree of agricultural intensification and the associated farming techniques.[6] When population density is low, long fallow periods can be used as a low cost means of managing soil fertility. As the population grows, more intensive techniques of agriculture are used—that is, the land is cropped more frequently. The quantity of labor and other inputs must be increased in order to maintain the fertility of the soil.

The previous models of agricultural intensification have focused on the effect of population pressure on the land-labor ratio. The models do not directly address the issue of the frequency of cropping or, equivalently, how much of the available land is actually cultivated in a given time period. Consequently, they are unable to distinguish between extensive agriculture as a low labor input per unit of cultivated land and extensive agriculture as the infrequent cropping of a unit of land with long fallow periods as a means of managing soil fertility. Indeed, soil fertility is not included in the previous formal models of agricultural intensification.

Darity (1980) and Pryor and Maurer (1982) formalize the Boserup framework with a variation of a neoclassical growth model with one output, one input, labor, and a labor-augmenting factor. In Darity (1980) population growth is exogenous and agricultural output is a concave, exponential function of the 'effective labor supply'. While the labor supply at any given time is perfectly inelastic, the amount of effective labor depends upon an additional parameter, the labor augmenting factor. The nature of this labor-augmenting factor is not explicitly defined but it is given the interpretation of either capital (roundabout production) or technical progress.

The labor-augmenting factor changes over time in proportion to the difference between the exogenously given "socially accepted subsistence threshhold" average wage and the actual

average wage. The acutal wage rate is determined by the labor supply and the size of the wages fund. The savings rate is constant and so the wages fund changes in strict proportion to the agricultural surplus. Because of the constant savings rate, the model has a knife-edge property in that the economy either grows without bound, collapses into starvation, or just happens to follow the knife-edge between those two outcomes, depending upon the value of key parameters.

In this model, agricultural intensification is defined as an increase in the labor augmenting factor rather than a transition from long fallow periods to more frequent or continuous cropping periods. Intensification can occur with no population growth and there can be population growth without intensification. In addition, the initial level of intensification is not determined by a specific relationship between land and population but must be given exogenously.[7]

The Pryor and Maurer (1982) model is similar to the Darity model in many respects but it also incorporates a Malthusian population growth equation. The population feedback allows the existence of a steady state equilibrium. The rate of growth of population is a linear function of the difference between the actual income and a "reference" income and the determinants of the reference income are not specified. It is interesting that the steady state income level is below the reference income if there is an exogenous component to population growth and if the production function is strictly concave.

Various specifications of the intensification equation are examined and the labor augmenting factor is interpreted as "work intensity". There are two types of intensification: an increase in the number of hours a person works and the degree of roundaboutness of production. As in Darity (1980), the rate of intensification is proportional to the difference between the reference income and the actual level of income and there is no specification of what determines the

initial level of work intensity. That is, there is no behavioral description of how working hours are determined nor is the roundaboutness of production described. The analysis begins with the case in which all of agricultural production accrues to agricultural workers. In the case of a non-working elite, the specification of the the dynamics of the wages fund also differs somewhat from the specification in Darity (1980).

A more microeconomic perspective of agricultural intensification is presented in Robinson and Schutjer (1984) and Salehi-Isfahani (1988). Both models examine changes in the land-labor ratio which occurs in response to population growth. They differ in their interpretation of Boserup's analysis about the prospects for agriculture development in response to population growth.

Robinson and Schutjer (1984) generally argue that Boserup takes an optimistic view of the prospects for agricultural development, particularly in the later extensions of her work which incorporate a non-agricultural sector. They employ a diagrammatic analysis of population growth and agricultural production in which there is a choice among different agricultural practices. The production function for a particular technique is strictly concave with respect to labor input. Land extensive techniques are more productive than intensive techniques at low levels of labor input but the relative positions are reversed at high levels of labor input. Thus, there is a shift in agricultural technique when a population threshold is reached. The switch to a more intensive technique dampens, but does not reverse, the decline in the average product of labor as the population grows.

In order to generate an increase in labor's average product with an increase in population, Robinson and Schutjer (1984) must rely on an ad hoc arugment involving either technological progress or capital investment. They note that the "...average product of labor need not fall

as output rises, thanks to technolgical shifts triggered by population growth," but they do not specify the link between population growth and technological progress. In addition, as Salehi-Isfahani (1987, 1988) points out, Boserup's basic argument did not rely on the development of new techniques and that there was often a shift back to less intensive techniques in response to a decline in population. In the Robinson and Schutjer model, the new technique (production function C in their Figure 1) is superior to either of the original production functions and there would be no return to the previous extensive technique if the population declined.

Salehi-Isfahani (1988) takes an approach similar to the Robinson and Schutjer (1984) model, but makes a more careful distinction between technical change, a change in factor proportions in response to a change in relative scarcity, and technological change, a shift in the production function, and reaches a much different conclusion. Salehi-Isfahani insists that labor productivity must decline as population increases and more land-intensive techniques are used and argues that Boserup also recognized this decline in labor productivity as population increases. By definition, more intensive techniques are inferior to extensive techniques because they require more labor per unit of output. The intensive techniques are employed only as a result of population pressure. Salehi-Isfahani also notes that the ability to use two different convex technologies simultaneously implies that the production technology is convex but not strictly convex.[8] This can slow, but not stop or reverse, the decline in labor productivity which accompanies agricultural intensification.

Salehi-Isfahani (1988) also adds a model of utility maximizing consumers who face this production technology. Because of the convex technology, the individual's budget constraint shifts inward as the population grows. The individual can adjust by consuming less and/or

working more. If two production techniques are in use simultaneously, then leisure unambiguously declines and an increase in population results in intensification—a decrease in the land-labor ratio in this framework. This also occurs in the case of one technique if the elasticity of the marginal rate of substitution with respect to consumption is greater than one in absolute value. The conclusion is a pessimistic, Malthusian-type result that well-being declines in response to population growth in the absence of technological change.

All of the previous models have assumed a concave production function, that is, a convex production technology. Given this assumption, it the average productivity of labor must decrease as the labor input applied to a fixed amount of land increases. In the absence of capital accumulation or technological change, which is exogenous to the Boserup framework, the prospects for growth in per capita production are not good. This seems to run counter to the spirit of the Boserup analysis that population growth provides the opportunity for agricultural and economic development which otherwise would not occur.[9]

None of these previous models focus on the role of long fallow periods as a means of managing soil fertility. Land plays a static role in these models and there is no distinction between extensive farming as the continuous cropping of large tracts of land and extensive farming as the periodic cropping of only a portion of the available land. The intensification of agriculture is defined as an increase in the amount of labor used in combination with a given quantity of land rather than an increase in the frequency with which the land is cropped. In the latter case, there may not be any significant change in the amount of cultivated land per farmer at a given time as agriculture intensifies, although the farmer would expend more labor on the same amount of land in order to maintain soil fertility. Indeed, it seems that the individual farmer would like to limit the amount of land under cultivation at a given time in order to

reduce the travel time to the fields (Stryker, 1976). This raises the issue of the role of land per capita apart from the dynamics of soil fertility and the soil management strategy.

The next section, which is based on the work of Lewis and Schmalensee (1975, 1977, 1979), demonstrates that if the net benefit to farming is strictly concave, then a continuous farming strategy is optimal. The continuous farming strategy would move either to a steady-state equilibrium or to the exhaustion and permanent abandonment of the land. If there are noncovexities in the net return function, then periodic cycles of farming and fallow can be the optimal strategy for managing soil fertility. The importance of the nonconvexity diminishes as the demand for food increases with population growth and a more continuous cropping strategy becomes optimal.

The incorporation of the dynamics of soil fertility and nonconvexities in the net benefit function are essential elements of a model in which agricultural intensification is defined as an increase in the frequency of cropping. Furthermore, if there are nonconvexities in the net benefit function, then an increase in the labor input and a higher average product for labor are not necessarily incompatible, particularly if there is a discrete switch from a less intensive to a more intensive agricultural technique.

## 3. The Soil Fertility Model

In general, the returns to farming depend upon the fertility of the soil and the application of labor and other inputs. The state of soil fertility could be described in a variety of ways—soil depth, soil moisture, the organic matter or nitrogen content of the soil, or a combination or index of relevant soil characteristics.[10] The state of soil fertility at time $t$ is denoted by $X(t)$.

If a given piece of land is left fallow, the fertility of the soil regenerates at a natural rate which can depend upon the current state of soil fertility. The state of soil fertility can affect the

soil's regeneration through the deposition of residue organic matter whose quantity can depend upon the level of soil fertility.[11] Consequently, the natural rate of regeneration of the soil can be low when soil fertility is low and then increase, reach a peak, and then decline as the soil fertility increases. This allows for both a maximum level of soil fertility and a minimum level below which any degradation of soil fertility is irreversible, such as occurs with desertification.

Let $g(X)$ denote the natural regeneration of the soil. That is, if the land is not cropped then the change in soil fertility is $\dot{X}(t) = g(X(t))$, where $\dot{X}(t)$ denotes the time derivative of soil fertility. It is assumed that there is a maximum level of soil fertility, $\tilde{X}$, such that $g(\tilde{X}) = 0$ and a level of fertility, $\underline{X}$, below which the soil does not regenerate so that $g(\underline{X}) = 0$. It is assumed that $g(X)$ is concave for $X \geq 0$.[12]

The net return to farming the land depends upon the current level of soil fertility and the specific farming technique which is employed. The farming technique can represent a schedule of various 'activities'—crop selection, tillage, etc.—which affect both the yield from the current level of soil fertility and the depletion of soil fertility. Thus, the net returns to farming can be written as a function of the depletion of soil fertility. Let $s(t)$ denote the depletion of soil fertility at time $t$ and let $B(X, s)$ denote the net return to farming.[13] It is assumed that there are positive but diminishing marginal returns to soil fertility and soil depletion (farming activity)—that is, $B_X > 0$, $B_s > 0$, $B_{XX} < 0$, $B_{ss} < 0$, and $B_{Xs} \geq 0$. It is assumed that farming is desirable at some time so that there exists an $s(0)$ such that $B(X(0), s(0)) > 0$.

Since farming the land depletes soil fertility, the time derivative of soil fertility—that is, the equation of motion—becomes $\dot{X}(t) = g(X(t)) - s(t)$. The net benefit function and the equation of motion capture the trade-off between current net benefits and future agricultural productivity.[14] The optimal management of soil fertility 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:

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

subject to:

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

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

where $\delta$ denotes the rate of discount.[15]

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 fertility and represents the current value shadow price, or marginal value, of soil fertility and the $\alpha_i$'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) requires that the marginal net benefit of soil depletion is equal to the marginal value of soil fertility at each point in time along the optimal path—that is, the flow and stock values of soil fertility are equal at the margin. Equation (6) governs the rate of change in the marginal value of soil fertility so that the rate of return to soil fertility is equal to the rate of discount and therefore to the rate of return to other assets.

Differentiating equation (5) with respect to time and using equation (6) yields the time derivative of the optimal path for soil depletion:

$$\dot{s}(t) = \frac{(\delta - g'(X))\lambda - B_X - B_{Xs}(g(X) - s)}{B_{ss}} \tag{7}$$

The denominator of equation (7) is negative. The numerator is positive when $\lambda$ is increasing and soil fertility is decreasing. In this case, then, soil depletion is decreasing over time.

The transversality, or boundary, conditions are:

$$X(T) \geq 0, \ \lim_{t\to\infty}\lambda(t) \geq 0, \quad \text{and} \quad \lim_{t\to\infty} e^{-\delta t}\lambda(t)X(t) = 0. \tag{8}$$

The transversality condition implies that either the soil fertility is exhausted or the present value of the shadow price for soil fertility goes to zero over the infinite time horizon.

The optimal path $s^*(t)$ satisfies equations (5) and (6), the initial condition $X(0) = X_0$, the non-negativity conditions, and the transversality conditions. 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 function.

With an infinite planning horizon, the optimal path can be to go to a steady-state equilibrium. A steady-state equilibrium is defined by $\dot{\lambda} = \dot{X} = \dot{s} = 0$, 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 soil fertility and the steady state soil depletion, respectively. Static efficiency requires $\lambda = B_s(X,s)$. Therefore, the steady state of soil fertility, $\bar{X}$, is defined by the condition:

$$\frac{B_X(\bar{X}, g(\bar{X}))}{B_s(\bar{X}, g(\bar{X}))} + g'(\bar{X}) = \delta \tag{9}$$

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

Total differentiation of equation (9) yields:

$$\frac{d\bar{X}}{d\delta} = \frac{-B_s}{(\delta - g')[B_{ss}g' + B_{Xs}] - g'B_{Xs} - B_{XX} - B_s g''} < 0 \tag{10}$$

if $\bar{X}$ is a stable equilibrium. Soil fertility in the steady-state equilibrium is inversely related to the rate of discount. Indeed, there is a rate of discount which is great enough for which it is optimal to exhaust soil fertility.

If a steady-state equilibrium exists, then soil fertility is monotonically decreasing and its shadow price is monotonically increasing along the optimal path when the initial soil fertility is greater than the steady-state level.[16] The movement of the state and costate variables is reversed if the initial soil fertility is less than the steady-state level. If the net benefit function, $B(X,s)$, is strictly concave everywhere, then the optimal strategy is either to move to a steady-state equilibrium or to ultimately exhaust the soil fertility, depending upon the own rate of return to soil fertility, $B_X + g'$, relative to the rate of discount.

## 4. Nonconvexities and Farming/Fallow Cycles

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—periodic cycles of farming and fallow which yields a higher present value. 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 activity, or if there is a discontinuity in the equation of motion when farming occurs.

In the case of a fixed cost to farming, 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. The fixed cost of

farming could include the cost of preparing the field and the level of fixed cost could depend upon the level of agricultural intensity.[17] If the net return to farming declines sufficiently as soil fertility declines, then the net benefits of farming may become negative for all rates of soil depletion—see Figure 1. In this case, the farmer is clearly better off by avoiding the fixed cost of farming by not planting a crop and letting the fertility of the soil regenerate before planting a crop in a later year. The opportunity cost of farming can include forgone returns, such as fuelwood and forage, which are available if the land is in forest or bush fallow.[18]

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 activity (and therefore soil depletion). This could arise because because of a minimum level of soil fertility required for a positive yield or because the marginal productivity of the soil is increasing over some range of activity.

A nonconvexity in the Hamiltonian, rather than the net benefit function, occurs if there is a minimum level of soil depletion, denoted $\sigma$, when the land is farmed. That is, if $s(t) \geq \sigma > 0$ when the land is farmed but $s(t) = 0$ if the land is fallow. This could occur, for example, because the removal of the natural vegetative cover exposes the topsoil to erosion. The effect of this jump in soil depletion is similar to the effect of a fixed cost of production equal to $\lambda\sigma$. However, in this case, the fixed cost of farming is endogenous since the marginal value of soil fertility is endogenous. If $\lambda$ was constant, then the effect would be identical to a constant fixed cost to farming. Since $\lambda$ is inversely related to soil fertility, this 'fixed cost' of farming increases as soil fertility is depleted.

In the presence of nonconvexities, the optimal soil management strategy can be cycles of farming and fallow. Indeed, there are conditions which are sufficient to insure that such

a cyclical farming strategy is optimal. The most straightforward case is when there is a fixed cost to farming. The fixed cost model can be viewed as a first approximation to the other nonconvexities. The discussion here follows that of Lewis and Schmalensee (1975, 1977, 1979) which establishes sufficient conditions for the optimality of a cyclical harvest of a renewable resource.

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 level of soil fertility for which it is possible to have non-negative net benefits, inclusive of the fixed cost. If the fertility of the soil falls below this level, then it must be better to not plant a crop. If this occurs, then the option is to abandon the land or to return to farm the land at a later date when the soil fertility has sufficiently regenerated to overcome the fixed cost of farming. Whether or not permanent abandonment is optimal depends upon the cost of returning to farm the land, which is denoted by $R$.

The most interesting case is when the cost of returning to farm the land is positive but finite.[19] In this case, sufficient conditions for it to be optimal to have farming and fallow cycles are given by: (a) the net benefit (including the fixed cost) from farming at the steady-state of the continuous farming strategy, $\bar{X}$, is negative ($B(\bar{X}, g(\bar{X})) \leq F$); (b) there is a level of soil fertility 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 of soil fertility such that 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 $X < \bar{X}$ such that $V_a(X) > R$ where $V_a$ denotes the discounted net benefit from an optimal abandonment strategy beginning at $X$ (Lewis and Scmalensee, 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 fallow is the better choice. However, the (temporary) abandonment of the land occurs at a viable level of soil fertility (condition b) and soil fertility regenerates while the land is fallow. Eventually, the soil fertility reaches a level at which the present value of farming the land 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 to return the land to fallow and the cycle repeats itself.

Lewis and Scmalensee (1979) point out that these sufficient conditions for the optimality of cyclical exploitation of the resource 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. Cycles of farming and fallow are preferred to continuous farming if the present value of the increased productivity from the higher soil fertility after a fallow period is greater than the present value of the net benefit foregone while soil fertility regenerates during fallow. 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 essence, the fallow periods can be the least cost means of managing soil fertility. The globally optimal strategy for a specific case would have to be determined by a comparison of the present values for each farming strategy.

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. A farming cycle, then, is defined by the state of soil fertility at which

farming is stopped, denoted by $X^S$, and the level of soil fertility at which farming resumes, denoted by $X^R$. The cycle interval is then defined to be $[X^S, X^R]$.

The level of fixed cost affects the optimal length of the farming and fallow cycles. A decrease in fixed cost increases the optimal amount of time spent farming the land (Lewis and Schmalensee, 1979, Proposition 3) and decreases the level of soil fertility at which farming is resumed (Lewis and Scmalensee, 1979, Proposition 5). Consequently, a decrease in fixed cost results in agricultural intensification in the sense that the land is cropped more frequently. In the next section, these comparative dynamic results are used to examine the effect of population growth on agricultural intensification.

## 5. Population Growth and Agricultural Intensification

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. Population growth and expanding markets affect the economic factors which determine the optimal farming strategy. Population growth increases the demand for food and the price, or value, of agricultural commodities will increase relative to the cost of production. The increase in the value of agricultural commodities increases the net return to farming for a given level of soil fertility and soil depletion. This tends to reduce the importance of the nonconvexity associated with the fixed cost to farming, the fixed cost of soil enhancement activities, or discontinuities in the regeneration of soil fertility 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.

The effect of an increase in the net benefit from farming which results from the greater demand for food is approximately the same as the effect of a decrease in fixed cost. Since

a decrease in fixed cost increases the frequency of cropping, an increase in the net return to farming has the same effect. Essentially, the higher return to farming reduces the importance of the nonconvexity in that it reduces the range of values for soil depletion for which the net benefit from farming is not concave. It also increases the net benefit from farming in a steady-state and so it is 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 an increase in the value of agricultural commodities and so the analogy is not exact—see Figure 2. A decrease in input costs would cause a similar upward shift of the net benefit curve.

Thus, agricultural intensification, defined as an increase in the frequency of cropping a given hectare of land, can be viewed as a change in the optimal farming strategy for soil management in response to an increase in the value of agricultural production resulting from population growth. Another interpretation is that as the population grows, the opportunity cost of fallow land increases and it becomes more economical to use intensive agricultural techniques to manage soil fertility. In any case, some kind of nonconvexity in the net benefit function is necessary in order for population growth to result in more frequent cropping rather than simply a change in the amount of input applied to a continuously cropped hectare of farmland.

Total agricultural output will increase with agricultural intensification as will the amount of labor required to maintain soil fertility. If the net return to farming is a concave function of labor input, then the average productivity of labor must decline as the labor input increases. However, if there is a nonconvexity in the net benefit function, then it is possible that the

average product of labor does not decrease in response to an increase in the amount of labor applied to a given hectare of land.

For simplicity, consider the case in which there are two farming techniques, one which uses long fallow periods in order to maintain the soil, and a 'more intensive' continuous cropping technique in which soil fertility is maintained through a greater application of labor. Also suppose that there is a fixed cost to farming. The less intensive, fallow technique will incur the fixed cost of farming less frequently. In addition, the more intensive, continuous cropping technique may have a higher fixed cost for one farming period if there are additional fixed costs—such as labor investments in land improvements—to more intensive techniques for soil management. One possible situation is depicted in Figure 3.[20] The less intensive, fallow technique is more productive for low inputs of labor, but the more intensive, continuous farming technique is more productive for high levels of labor input. If labor input is proportional to population, then the long fallow technique is used when the population is small and a switch to continuous cropping is made when the population reaches a certain size.

Given that the fixed cost of farming induces a nonconvexity in the production function for a given farming technique, the average productivity of labor for that technique can be rising over some range of labor input. If the production function is concave apart from the fixed cost, then eventually the average productivity of labor for the chosen technique will decline as the labor input increases. However, the average productivity of labor in agriculture can increase, at least over some range of labor input, after the switch to the more intensive technique is made in response to the population growth. This occurs in the specific case depicted in Figure 3.

The possibility that the average productivity of labor in agriculture will increase with the adoption of more intensive farming, even in the absence of technological change, gives a

more optimistic perspective on agricultural development than in the previous formal models of agricultural intensification induced by population growth. Of course, whether the average productivity of labor increases or decreases with agricultural intensification is an empirical question. Boserup (1965, 1981) generally viewed the productivity of labor as decreasing with intensification so that intensive techniques are not used until population pressure necessitates their adoption, but some remarks indicate that labor productivity could increase with some types of intensification, particularly irrigated multi-cropping. In any case, the average labor productivity with intensive techniques would be greater than the average productivity of the same amount of labor using extensive techniques.

Boserup (1965, 1981) also emphasized the interaction between agricultural intensification and the development of the non-agricultural sectors of the economy. Agriculture intensification resulting from increased population density provides a larger total agricultural surplus to support a high degree of urbanization even if the average surplus per worker declines. In addition, agricultural intensification leads to a more sedentary population. A more concentrated and sedentary population allows the economy to take advantage of returns to scale in other sectors of the economy. It is particularly helpful in overcoming the fixed costs associated with developing social and economic infrastructures since the per capita cost of supplying infrastructure is greatest when the population is small and widely dispersed. Thus, nonconvexities are also important in the development of the infrastructure of the economy.

The development of the transportation and marketing sectors and the ability to support investments in human capital, agricultural research and extension, have particularly important effects on the agricultural productivity by lowering the costs of obtaining industrial and scientific inputs—fertilizers, pesticides, extension services, etc.—and the cost of getting crops to market.

The use of industrial and scientific inputs can enhance labor productivity in agriculture so that output per man-hour does increase with more intensive agricultural techniques (Boserup, 1975).[21]

These improvements in agricultural productivity are available only with intensive techniques of agriculture. When the improvement in agricultural productivity associated with the development of other sectors of the economy is incorporated into the net benefit of intensive farming (i.e. frequent cropping), the nonconvexity in agricultural production at the switching point from extensive to intensive technology is even more pronounced and there is a greater likelihood that the average productivity of labor will increase in response to agricultural intensification. If this is the case, then population growth is necessary for it to be economical to capture the productivity gains from agricultural intensification rather than agricultural intensification being a necessary response to population pressure.[22]

The advantageous contributions of population growth to agricultural development are obtained through the mechanism of the increased value of agricultural commodities. If the price (or value) of these commodities is kept artificially low, then there is insufficient incentive for the necessary investments in land improvements and rural infrastructure and the possible gains from agricultural intensification are not achieved. Unfortunately, agricultural policies such as subsidies and price supports in developed countries and price ceilings in developing countries may have had this type of negative impact on agricultural development in some countries (Boserup, 1987).

In summary, a nonconvexity in the net return to farming is an essential, indeed necessary, element in explaining the transition from land extensive, long fallow techniques of cultivation to more labor intensive continuous cropping techniques. Because of the nonconvexity in net

returns to farming, it is possible to reconcile the greater labor requirement of intensive farming methods with a higher average labor productivity in agriculture as the population increases. The prospects for increased agricultural development in response to population growth are enhanced by the development of the non-agricultural sectors which contribute to the productivity of agriculture.

## Notes

[1]The causal relationship running from population density to farming technique rather than vice versa is supported by several historical cases in which a population decrease resulted in a return to less intensive farming strategies. Boserup, (1981) cites the examples of Mesoamerica (p. 55), European settlers in the New World (p. 135), and post-World War II Japan (p. 170).

[2]Darity (1980) lists a "clear repudiation of Malthusian population pessimism" as one of the important differences between Boserup's view and older perspective. Boserup (1965, p. 14, 21-22) also rejects the neo-Malthusian view that increased population necessarily leads to the destruction of land. Boserup places a heavy emphasis on the economic and sociological changes which follow in the wake of agricultural intensification.

[3]There has been at least one test the empirical implications of the Boserup analysis. Levi (1976) conducts an empirical investigation of the relationship between population density and agricultural intensity in Sierra Leone. He finds that population density is not necessarily a good measure of population pressure since population density can be the result of migration to areas with particularly productive land or areas which are desirable for other reasons. Instead, the study uses actual to potential output—as measured by the ratio of population to labor force (the dependency ratio)—as a measure of population pressure on the land. The findings are generally consistent with the Boserup hypothesis, including a negative correlation between population pressure and the length of the fallow period and a small positive correlation between the adoption of swamp farming (continuous farming) and population pressure.

[4]Robinson and Schutjer (1984) are more optimistic about the prospects for agricultural development. They note that, "The basic point of view is optimistic and stresses that most rural societies have an unrealized potential for further technological adaptation, if and when population pressure begins to build up." Their optimistic results rely upon either technological progress or the development of an urban industrial sector which can supply the inputs necessary for agricultural intensification.

[5]An investment of labor in land improvements is important: "...the land-saving systems usually cannot be applied without some preliminary labor intensive land improvements. ...clearing roots and stones from land before it can be plowed,... building wells, ponds, dams, terraces, bunds, and so on, for irrigation. Once such labor investments have been made, it may be possible to obtain higher output per man-hour from the cultivation of permanent fields than from long-fallow agriculture on similar land.... (Boserup, 1976)." Boserup relied more on the growth of a non-agricultural sector in the wake of agricultural intensification as the source of increased labor productivity in agriculture.

[6]Boserup (1965, p. 13) notes, "The very distinction between fields and uncultivated land is discarded and instead emphasis is placed on the frequency with which the land is cropped. ...Once the time-honoured distinction between cultivated and unclutivated land is replaced by the concept of frequency of cropping, the economic theory of agricultural development becomes compatible with the theories of changing landscape propounded by natural scientists. ...when the analysis is based on the concept of frequency of cropping, there can be no temptation to regard soil fertility exclusively as a gift of nature, bestowed upon certain lands once and for all. Thus, soil fertility, instead of being treated as an exogenous or even unchangeable

'initial condition' of the analysis, takes its place as a variable, closely associated with changes in population density and related changes in agricultural methods." She also notes that fallow lands, "...have the functions of recreating soil fertility or humidity, preventing erosion, or suppressing troublesome weeds before the land is again used for crops (Boserup, 1987)."

[7]Indeed, land is not explicitly included in the model.

[8]This is not a major innovation. As Salehi-Isfahani notes, as the number of techniques increases, the flat spots on the 'meta-isoquant' become less relevant.

[9]Boserup (1965) notes that "...primitive communities with sustained population growth have a better chance to get into a process of genuine economic development than primitive communities with stagnant or declining, population, provided of course, that the necessary agricultural investments are undertaken."

[10]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 (1987). 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.

[11]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.

[12]The case of a constant rate of soil regeneration, $g(X) = k$, which is common in the soil conservation literature, is examined in Krautkraemer (1990).

[13]An alternative formulation of the model could specify a level of farming activity, say $u(t)$, as the control variable and the depletion of soil fertility would be a function of the level of farming activity, $s(t) = f(u(t))$. In the present formulation, the relationship between farming activity and soil depletion is embedded within the net benefit function. The formulation used here simplifies the exposition of the cyclical farm strategies. The formulations are the same when there is a monotonic relationship between farming activity and soil depletion. McConnell (1983) also uses soil depletion as the control variable. Krautkraemer (1987) develops the current model with farming activity as the control variable.

[14]This implicitly assumes that the schedule of farming activities is monotonic. That is, if $s = f(u)$, as in the previous footnote, then $f'(u) > 0$ so that $\partial B/\partial u > 0$. There are farming activities which can enhance soil fertility at some cost. 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 depletion and increases the net return to farming would represent a technological improvement.

[15]An infinite planning horizon is used in order to avoid the need to specify a terminal value for soil fertility. 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 and so an infinite time horizon is used here.

[16]The steady-state equilibrium may not be unique. The initial level of soil fertility then determines the optimal steady-state. It is possible that exhaustion is optimal for some initial values of soil fertility while movement toward a steady-state with positive soil fertility is optimal from other initial values for soil fertility.

[17]Many of the additional labor requirements associated with more frequent cropping can be characterized as fixed costs.

[18]"During fallow periods, the land is used for a variety of purposes: for gathering fuel and other wood, for hunting, for gathering of fertilizer, for grazing and browsing by domestic animals. therefore, a change of the falow system may create unintended damage to the environment unless substitutes are introduced for these commodities, or the pattern of consumption is changed (Boserup, 1987)."

[19]If returning to the land to farm is not possible, then abandonment must be permanent. It may be that the soil fertility 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 level of soil fertility to be sustained. 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. In a continuous time framework, if returning to farm the land is costless, 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).

[20]This diagram is much like the diagram in the upper right-hand quadrant of Figure 1 in Robinson and Shutjer (1984) but the fixed cost creates a nonconvexity in the production technology.

[21]Boserup (1975, p. 262) notes that "...an expansion of output by means of modern inputs raises agricultural output at a rate that is significantly higher than the rate of increase of input of agricultural labor."

[22]This may be what Robinson and Schutjer (1984) have in mind with production function C in their Figure 1 although this figure does not reflect that the productivity enhancing effects of the urban industrial sector are not available at low levels of population density. A nonconvex production technology is necessary in order to have higher average productivity with greater population density.

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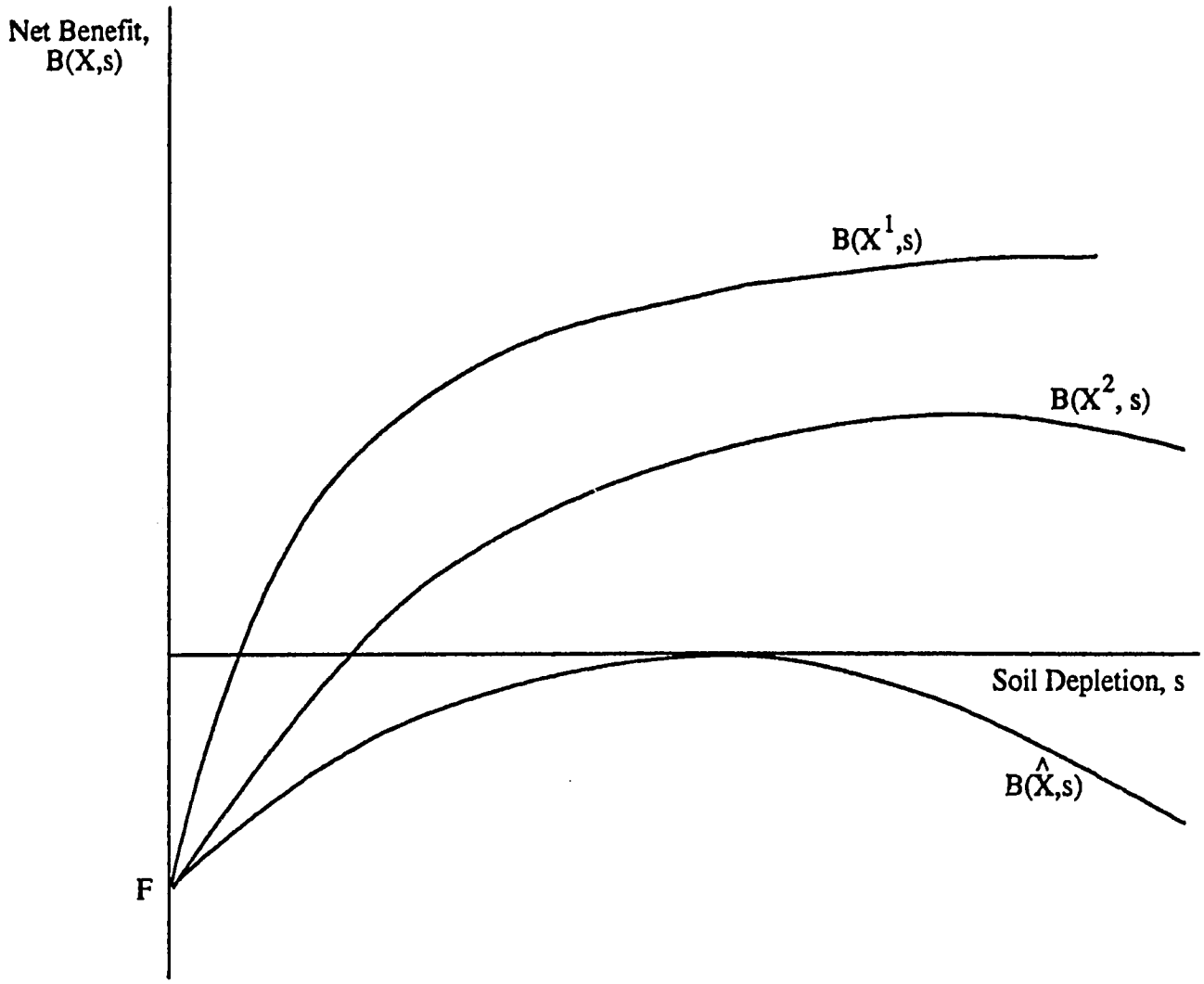


**Figure 1**

Net Benefit Function with Fixed Costs, F
$X^1 > X^2 > \hat{X}$

As soil fertility declines, the net return to farming, including the fixed cost of farming, declines and may become non-positive for any level of soil depletion (farming activity). The state of soil fertiliy at which there can be no positive return to farming is denoted by $\hat{X}$.

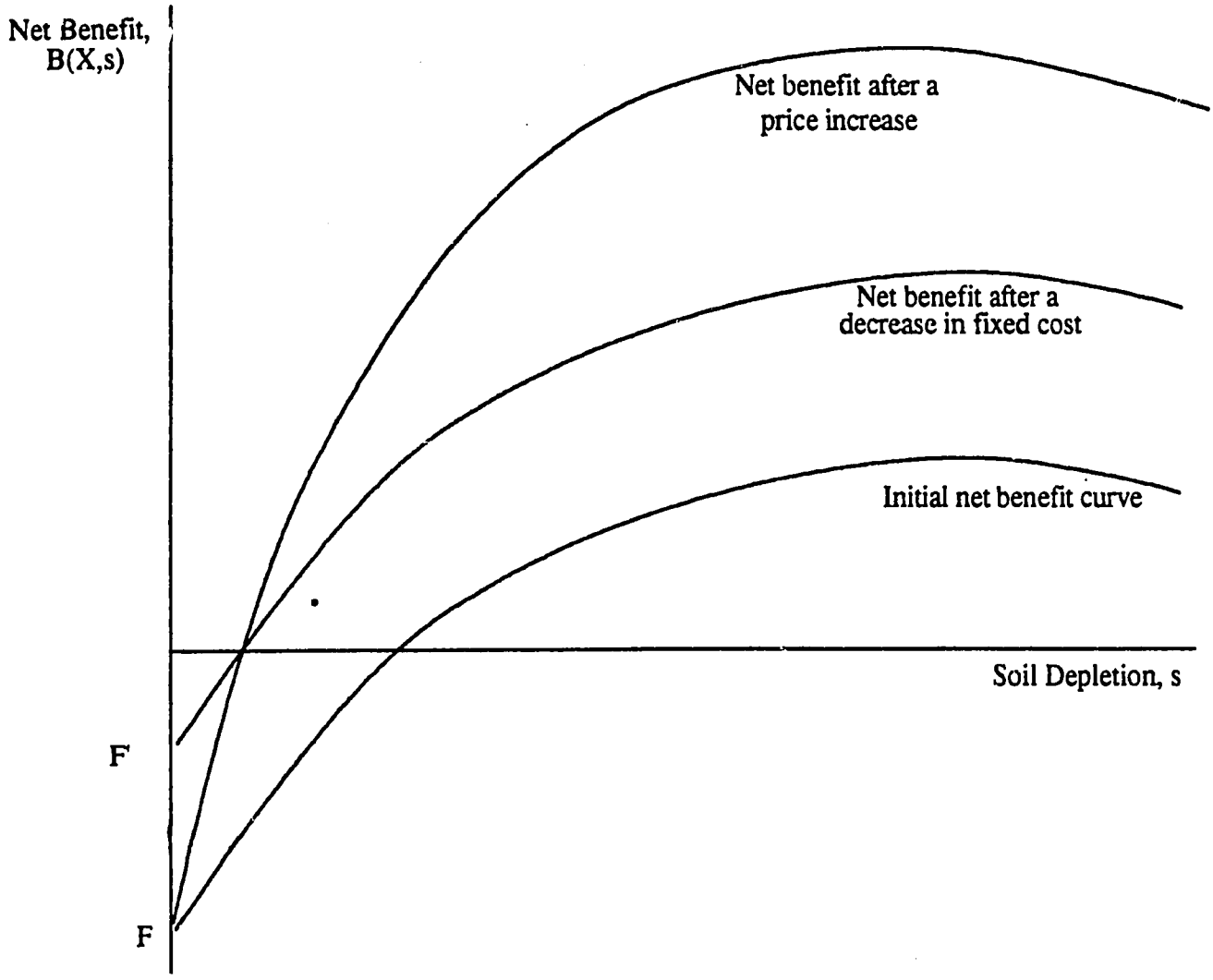


**Figure 2**

The effect of a price increase, or increase in the value of agricultural output is compared to the effect of a decrease in fixed cost. Both changes reduce the relative importance of the nonconvexity--that is, the interval of soil depletion (farming activity) levels for which the net return function is not concave.

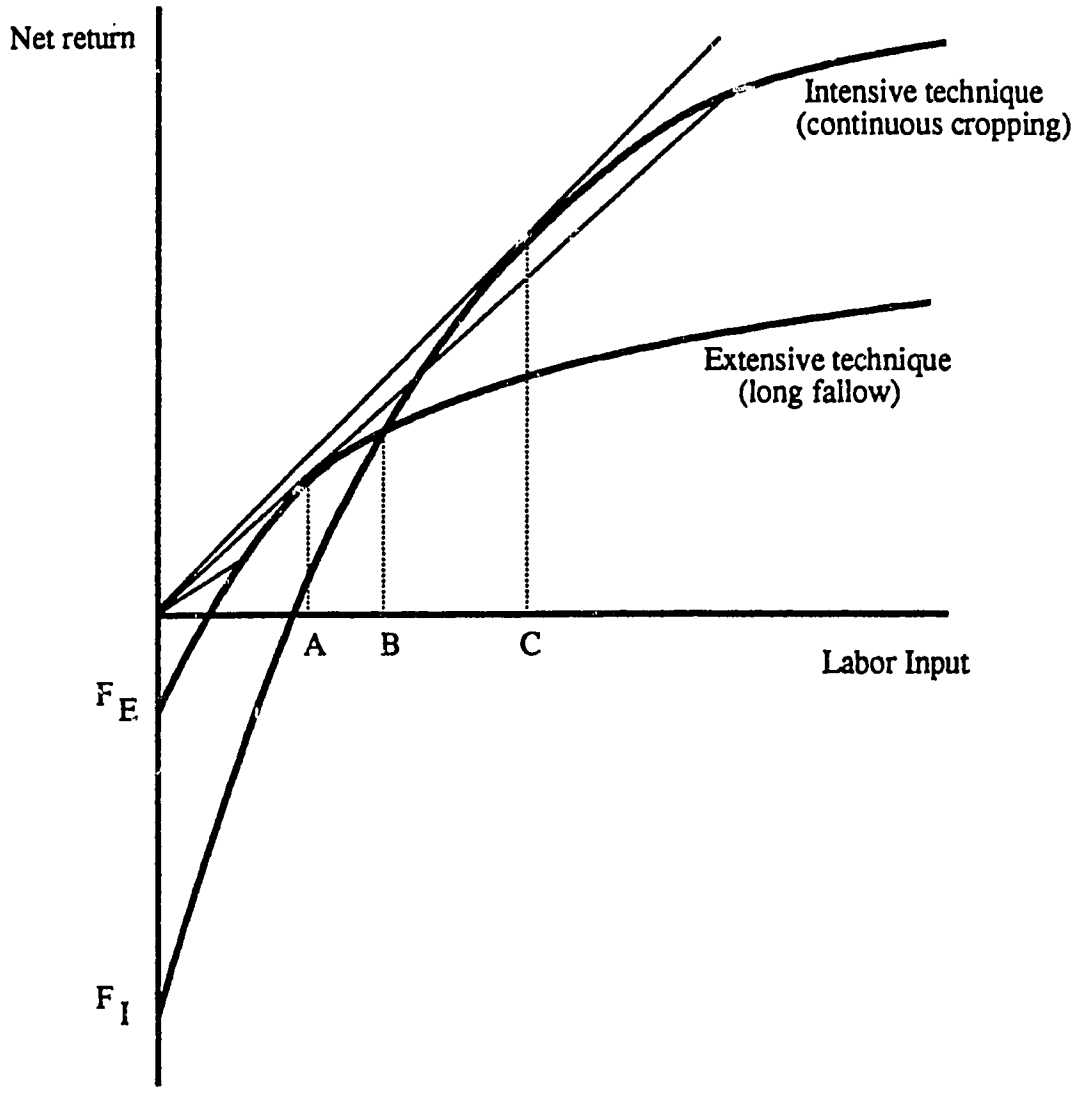


**Figure 3**

This diagram depicts the net benefit curve for extensive and intensive agricultural techniques with fixed cost $F_E$ and $F_I$, respectively. In the case depicted, the average productivity of labor decreases from point A to point B but increases from B to C after the transition to continuous cropping.

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