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Agricultural Price Policies and Soil Conservation: A Steady State Comparative Static Analysis

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ABSTRACT. There are contradictory theoretical claims on the effects of agricultural price policies on soil conservation. This paper develops a dynamic model of soil conservation and carries out a steady state comparative static analysis. Results show that price effects on soil conservation are more complex than previously shown. Agricultural output price and price of soil conservation measures have indeterminate effect on soil conservation. The results, thus, cast doubts on the effectiveness of soil conservation subsidies. Higher input price and lower discount rates promote soil conservation. Since some of the price effects are indeterminate and strong assumptions are necessary to sign the other comparative static results, agricultural price policies may not be a promising means to achieve soil conservation objectives.

INTRODUCTION

Soil erosion is slowly undermining about one third of the world's crop lands (WCED, 1987). Although the data on the magnitude of the soil erosion at the global level is far from complete, the available information shows that every year the world's farmers lose an estimated 24 billion metric tons of top soil from their crop lands in excess of new soil formation (Buccholz, 1993). In addition to the on-site cost of soil erosion, sediments transported and deposited in reservoirs often cause severe economic and environmental damages. For example, the world will lose nearly one third to two thirds of its reservoir capacity by the year 2000 (Younis and Dragun, 1993). Thus, the economic life span of very expensive infrastructure assets are being impaired at a rather fast rate due to soil erosion. Although the above quoted estimates are not very precise, they indicate the gravity of the soil erosion problem and the need for urgent measures to arrest soil erosion.

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Many analysts contend that solutions to the soil erosion problem must be sought within the upland areas using new technologies, altered agricultural practices, reduced immigration, provision of conservation subsidies, more secure tenure rights, and strong legislative measures (Coxhead and Jayasuriya, 1995). While these approaches are undoubtedly important, they seem to overlook the impact of macro-economic policies on farmers' decisions on soil conservation levels. This paper focuses on the impact of agricultural price policies on soil conservation. Most of the developing countries are currently undergoing economic reforms that are aimed at conversion of their economies to efficient market economies with the help of the World Bank and the International Monetary Fund. Developing countries generally tax their agricultural products, and that keeps agricultural prices at artificially low levels. Removal of distortions on agricultural prices is an important part of the current economic reforms. According to some schools of thought, lower agricultural prices depress agricultural activities and hence decelerate soil degradation. Those with the above view of removal of the existing taxes under the current economic reforms, as detrimental to soil resources. Theoretical economic analysis on the subject, however, is so far inconclusive, and the analysis presented in this paper attempts to partially fill the existing gap.

There is adequate evidence in the literature to support the view that price policies have a significant impact on agriculture in developing countries (Askari and Cummings, 1977; Repetto, 1987; Roumasset and Setboonsrang, 1988). However, the impact of changes in related prices on soil conservation has not been studied adequately and controversial claims on such impacts are presently prevalent in the literature. For example, Repetto (1987) argues that higher agricultural prices would encourage soil conservation. His argument is, briefly, that higher prices provide better returns to both crops and conservation measures, and thus provide incentives for soil conservation. On the other hand, Lipton (1987) asserts that since higher agricultural prices provide incentives to mine the soil, farmers tend to cultivate intensively and make short term profits while eroding their soils. The first type of argument views soil as a capital asset such that farmers tend to invest on it, *i.e.*, to practice soil conservation, when the returns to this asset are high. The second type of argument views soil as a non-renewable resource such that farmers tend to maximize their returns by mining the soil when prices are high. As elegantly summarized by LaFrance (1992), though both these arguments have flaws, they are generally correct. These two opposing forces add to the complexity of the problem since they jointly govern the soil resource use decisions by farmers.

Barrett (1991), LaFrance (1992), and Clarke (1992) are recent theoretical studies which address the impact of agricultural price policies on soil conservation. Using a dynamic economic model, Barrett (1991) shows that the soil conservation level is independent of the agricultural output and input prices. Clarke (1992) uses a similar model to show that any price change that augments farm profits promotes soil conservation provided that there are economically viable conservation methods. In contrast, LaFrance (1992) shows that soil conservation depends upon agricultural prices, but the effect can go either way depending on dominance of the effect of cultivation and the effect of conservation. Thus, there are contradictory theoretical claims on the impact of agricultural prices on soil conservation.

This paper develops a dynamic soil conservation model borrowing elements from McConnel (1983) and LaFrance (1992) and carries out a steady state comparative static analysis to examine the effect of price changes on soil conservation. Some of the unrealistic assumptions of the previous work were changed to incorporate the impact of conservation on crop productivity more accurately. For example, LaFrance (1992) considers cultivation as a crop improving and land degrading activity and conservation as a crop reducing and soil conserving activity. Cultivation is certainly a crop improving and soil degrading activity. Nevertheless, conservation, although it reduces crop yields immediately as a result of using up some amount of land and other resources, may not be crop reducing in its overall effect. Because conservation measures not only the extent of soil retained physically, but also the improvement of soil's physical properties, especially the soil moisture retention capacity, these improved physical properties have a positive impact on crop production. This immediate negative and consequent positive effect of soil conservation on crop yield is properly incorporated in the present analysis.

Barrett (1991), Clarke (1992), and LaFrance (1992) use infinite horizon dynamic models in their analyses. If the dynamic optimization problem has an infinite horizon and is autonomous, it is normally assumed that the system approaches a steady state as $t \rightarrow +\infty$. Thus, the infinite horizon models allow use of steady state solution to obtain qualitative properties (Caputo, 1992). However, since private individuals have shorter planning horizons (McConnell, 1983; Dixon and Hufschmidt, 1986; Griffin and Stoll, 1986) using an infinite planing horizon economic models to study individual responses to price changes may be unrealistic. The present study uses a finite planning horizon model which represents the individual responses on soil conservation for price changes more accurately. Instead of relying on an infinite horizon for the steady state, the present analysis checks the stability properties of the steady state in the finite horizon model.

The rest of the paper is organized as follows. The second section of the paper outlines the dynamic model and derives and interprets the optimality conditions. The third section verifies the stability of the steady state and carries out comparative dynamic analysis. The final section presents the policy implications.

THE MODEL AND THE OPTIMALITY CONDITIONS

Assume a representative farmer who cultivates his crops in an erosion prone area. Although the farmer can cultivate many crops, for simplicity, it is assumed that the farmer cultivates a single crop. This assumption avoids the unnecessary complications that could arise from crop rotations, fallow periods, etc. Results of the analysis, however, can be readily generalized to a many crop situation. The farmer's production function for the single crop is represented by:

(1) $q(t)=q(x(t), y(t), s(t))$

where $q(t)$ is the quantity of output at time t, $x(t)$ is the rate of cultivation at time t, $y(t)$ is the rate of soil conservation at time t, and $s(t)$ is the stock of soil at time t. $x(t)$ can be interpreted as the percentage of the land brought under cultivation at time t. Similarly, $y(t)$ represents the extensiveness of the adopted soil conservation measures. It can be measured as the percentage of the land under proper soil conservation measures or the number of meters of terraces or similar conservation measures on the farm. The agricultural production function is assumed to be a twice differentiable function. The assumptions regarding the derivatives of equation 1 are given by:

(A1) $q_x>0,\ q_y<0,\ q_s>0$,

(A2) $q_{xx}<0, q_{ss}<0, q_{yy}>0$, and

(A3) $q_{xy}>0,\ q_{xs}=0,\ q_{sy}=0$.

A1 implies that agricultural production increases as cultivation increases. Using more conservation measures, which consume some amount of land for terracing or hedgerows, reduces the output. This reduction of output can occur due to allocation of some scarce labor for soil conservation instead of cultivation. Higher stock of soil provides a greater quantity of output because it provides more nutrients and more space for root growth. The first two derivatives in A2 imply that there is diminishing marginal returns of agricultural output for the incremental changes in rate of cultivation and the soil stock. In the case of cultivation, the diminishing marginal returns may occur due to the push of the cultivation area to less productive lands. Increasing the soil stock beyond a certain level may not bring much impact on productivity since the crops normally use only the root zone and a limited quantity of nutrients. Therefore, the soil stock provides diminishing marginal returns. The third derivative in (A2) suggests that the negative impact of conservation diminishes as more conservation measures are in place.

Although the adoption of conservation measures immediately reduces crop yields, improvements of moisture retention capacity and other physical properties of soil will have a positive impact on productivity. Therefore, the negative impact of the rate of conservation on agricultural output diminishes as more conservation practices are in place. For the same reason mentioned above regarding the second order derivative of the rate of conservation, it is reasonable to assume that the marginal productivity of cultivation increases as more conservation measures are in place as suggested by A3. These assumptions ($q_{yy}>0$ and $q_{xy}>0$) allow incorporation of the positive secondary impact of soil conservation on crop production[i]. It is assumed that marginal productivity of cultivation and stock of soil and the rate of soil conservation do not affect soil stock, respectively. These simplification assumptions on cross partials, although can be viewed as a limitation of the model, facilitates the comparative static analysis[ii].

Equation (2) expresses the dynamics of the change in the soil stock of the farm. L represents the function that governs the soil loss that depends on the rate of cultivation and the rate of conservation.

(2) $\dot{s} = K - L(x(t), y(t))$

where K is the soil formation which is assumed to be time invariant and L is the soil loss function. The assumptions with regard to the soil loss function are given by:

(A4) $L_x>0,\ L_y<0,\ L_{xx}>0\ L_{yy}<0\ L_{xy}<0$

A4 implies that more cultivation increases the soil loss while more conservation reduces the soil loss. The second order own partials suggest that the marginal impact of cultivation on soil loss increases as cultivation increases. This will happen when the farmer expands cultivation to marginal and more erosion-susceptible lands. The marginal impact of soil saving by conservation increases as more conservation measures are used on the farm. This effect is due to the reduction of the erosivity factor of soils as a result of improvement of physical and chemical properties by conservation measures. The second order cross partial implies that the soil losing impact of cultivation diminishes as more conservation practices are in place. The farmer's optimization problem can be represented as:

(3) $$V(\beta) = \int_0^T e^{-rt}[p^a q(t) - p^l x(t) - p^c y(t)]dt,$$

subject to $\dot{s} = K - L(x(t), y(t))$, and

and $s(0) = s_0$.

where, r is the discount rate, p^a is the price of agricultural product, p^I is the agricultural input price, p^c is the price (unit cost) of conservation measures, and $\beta = (p^a, p^I, p^c, r, k)$ is the parameter vector.

The associated current value Hamiltonian is:

(4)

$$H(x, y, \lambda, p^a, p^I, p^c, r, K) = p^a q(x(t), y(t), s(t)) - p^I x(t) - p^c y(t) + \lambda(K - L(x(t), y(t)))$$

where λ is the costate variable for the soil stock. Using Pontryagin's maximum principle, the necessary conditions for optimization were obtained. These first order necessary conditions are:

(5.1) $H_x = p^a q_x - p^I - \lambda L_x = 0$,

(5.2) $H_y = p^a q_y - p^c - \lambda L_y = 0$,

(5.3) $\dot{\lambda} = r\lambda - H_s = r\lambda - p^a q_s$, and

(5.4) $\dot{s} = K - L(x(t), y(t)), \ s(0) = s_0$.

Note that the above conditions are both necessary and sufficient conditions for the optimization given the concavity assumptions made earlier. Equation (5.1) shows that the farmer chooses his rate of cultivation at a point where the marginal benefit ($p^a q_x$) of cultivation equals the marginal cost. The marginal cost has two components; the first is the marginal cost of variable inputs (p^I) required by the extra lands brought under cultivation and the second is the marginal shadow cost (λL_x) incurred by losing soils due to cultivation. Similarly, equation (5.2) shows that the farmer chooses his rate of conservation at a point where the marginal benefit of conservation equals the marginal cost of conservation. The marginal benefit in this case is the shadow value of the conserved soil (λL_y) and the marginal costs are the values of the lost crop yields due to conservation ($p^a q_y$) and the direct cost of conservation (p^c). The latter includes the unit cost of labour and other inputs used in establishing and maintaining conservation measures. Equation (5.3) can be interpreted assuming that soil stock is a form of capital and that the farmer intertemporally allocates his soil capital in production at a point where marginal benefit is equal to marginal costs. This equation can be rearranged to yield $r\lambda - \dot{\lambda} = p^a q_s$. As such, the left hand side measures the cost of the two components of utilizing soil capital; $r\lambda$ represents the interest charge term and - $\dot{\lambda}$ represents the capital gains term. The right hand side term reflects the direct marginal gains of the soil capital in terms of agricultural production. Equation (5.4) represents the dynamics of the change in soil stock such that the change in soil stock is equal to the soil formation less the soil loss due to erosion.

RESULTS

This section uses equations (5.1) through (5.4) to carry out the steady state comparative static analysis. First, theorem 6 in Gale and Nikaido (1965) is used to solve equation (5.1) and (5.2) simultaneously for $\hat{x}=\hat{x}(\beta)$ and $\hat{y}=\hat{y}(\beta)$ where $\hat{\beta}=(p^a,p^l,p^c,\lambda)$. This reduces equations (5.1)-(5.4) to two differential equations and makes the comparative dynamic analysis easy. The stability of the steady state solution is then checked. Finally, equations (5.3) and (5.4) are solved simultaneously using the intermediate results obtained by solving equation (5.1) and (5.2) and assuming $\dot{\lambda}=0$ and $\dot{s}=0$. See appendix for the details of the solution for (5.1) and (5.2).

Stability of the steady state

By substitution of the results obtained in the appendix into equations 5.3 and 5.4, the following system of equations was obtained:

(5.3)' $\dot{\lambda} = r\lambda - p^a q_s(\hat{x}(t,\hat{\beta}), \hat{y}(t,\hat{\beta},s(t))$,

(5.4)' $\dot{s} = K\text{-}L(\hat{x}(t,\hat{\beta}),\hat{y}(t,\hat{\beta}))$.

The elements of the Jacobian matrix J for the above system evaluated at $\dot{\lambda}=0$ and $\dot{s}=0$ are given below.

$$\frac{\partial\dot{\lambda}}{\partial\lambda} = r > 0 \qquad \frac{\partial\dot{\lambda}}{\partial s} = -p^a q_{ss} > 0$$

$$\frac{\partial\dot{s}}{\partial\lambda} = -L_x\frac{\partial\hat{x}}{\partial\lambda} - L_y\frac{\partial\hat{y}}{\partial\lambda} > 0 \qquad \frac{\partial\dot{s}}{\partial s} = 0$$

The determinant of the J cannot be signed without a further assumption about $\frac{\partial \hat{y}}{\partial \lambda}$. It is assumed that the incremental effect of cultivation on soil loss dominates that of conservation ($L_x(p^a q_{xy} - \lambda L_{xy}) > L_y(p^a q_{xx} - \lambda L_{xx})$), and, therefore, $\frac{\partial \hat{y}}{\partial \lambda} > 0$ [iii]. With this assumption it is clear that determinant of the J is negative, and, hence, the steady state equilibrium is characterized by a saddle point. The implicit function theorem was applied and the intermediate results in appendix were used in deriving the slopes of the $\dot{\lambda} = 0$ and $\dot{s} = 0$ isoclines which are given below:

$$\frac{\partial \lambda}{\partial s}\bigg|_{\dot{\lambda}=0} = \frac{p^a q_s}{r} < 0 \qquad\qquad \frac{\partial \lambda}{\partial s}\bigg|_{\dot{s}=0} = 0$$

Figure 1 shows the stability of the steady state equilibrium of the problem presented in equation 3. As shown, the equilibrium is stable when $\dot{\lambda} < 0$ and $\dot{s} > 0$. When the state and the costate variables have the same direction of change the equilibrium becomes unstable. Intuitively, when the stock of soil increases, its shadow value should decrease, therefore, the equilibrium depicted in the phase diagram is in harmony with basic economic reasoning.

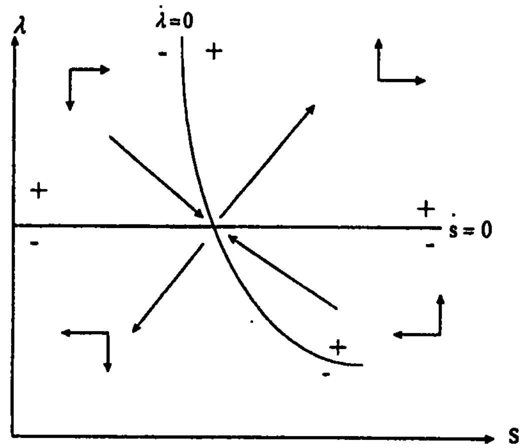

Figure 1. Phase diagram in the s, λ plane.

Steady state comparative statics

The effect of the changes in the parameters of the model on state and costate variables at the steady state are examined in this section. As shown above, the determinant of the Jacobian is negative, and the steady state solution is characterized by a saddle point. Therefore, by the implicit function theorem, the steady state of (5.3)' and (5.4)', in principle, can be solved uniquely for the state and costate variables, denoted by $\lambda = \lambda^{*}(\beta)$ and $s = s^{*}(\beta)$. Total differentiation of the system (5.3)' and (5.4)' yielded the following system of equations.

$$(6)\quad C + J\begin{pmatrix} \frac{\partial \lambda^{*}}{\partial p^{a}} & \frac{\partial \lambda^{*}}{\partial p^{I}} & \frac{\partial \lambda^{*}}{\partial p^{c}} & \frac{\partial \lambda^{*}}{\partial K} & \frac{\partial \lambda^{*}}{\partial r} \\ \frac{\partial s^{*}}{\partial p^{a}} & \frac{\partial s^{*}}{\partial p^{I}} & \frac{\partial s^{*}}{\partial p^{c}} & \frac{\partial s^{*}}{\partial K} & \frac{\partial s^{*}}{\partial r} \end{pmatrix} = 0.$$

where,

$$J = \begin{pmatrix} r & -p^{a}q_{ss} \\ -L_{x}\frac{\partial \hat{x}}{\partial \lambda} - L_{x}\frac{\partial \hat{y}}{\partial \lambda} & 0 \end{pmatrix}$$

$$C = \begin{pmatrix} -q_{s} & 0 & 0 & \lambda & 0 \\ -L_{x}\frac{\partial \hat{x}}{\partial p^{a}} - L_{y}\frac{\partial \hat{y}}{\partial p^{a}} & -L_{x}\frac{\partial \hat{x}}{\partial p^{I}} - L_{y}\frac{\partial \hat{y}}{\partial p^{I}} & -L_{x}\frac{\partial \hat{x}}{\partial p^{c}} - L_{y}\frac{\partial \hat{y}}{\partial p^{c}} & 0 & 1 \end{pmatrix}$$

Application of the Cramer's rule to the above system results steady state comparative static results for the costate variable. These results are presented in Appendix 3 and their interpretations are not included here for the brevity of the presentation. The more important comparative static results with respect to the changes in soil stock are presented and discussed below.

$$(7.1)\qquad \frac{\partial s}{\partial p^{a}} = \frac{r[L_{x}\frac{\partial \hat{x}}{\partial p^{a}} + L_{y}\frac{\partial \hat{y}}{\partial p^{a}}] + q_{s}[L_{x}\frac{\partial \hat{x}}{\partial \lambda} + L_{y}\frac{\partial \hat{y}}{\partial \lambda}]}{|J|} \gtrless 0,$$

$$(7.2)\qquad \frac{\partial s}{\partial p^{I}} = \frac{r[L_{x}\frac{\partial \hat{x}}{\partial p^{I}} + L_{y}\frac{\partial \hat{y}}{\partial p^{I}}]}{|J|} > 0,$$

$$(7.3) \qquad \frac{\partial s}{\partial p^c} = \frac{r[L_x \frac{\partial \hat{x}}{\partial p^c} + L_y \frac{\partial \hat{y}}{\partial p^c}]}{|J|} \lesseqgtr 0,$$

$$(7.4) \qquad \frac{\partial s}{\partial r} = \frac{\lambda[-L_x \frac{\partial \hat{x}}{\partial \lambda} - L_y \frac{\partial \hat{y}}{\partial \lambda}]}{|J|} < 0, \text{and}$$

$$(7.5) \qquad \frac{\partial s}{\partial K} = \frac{-r}{|J|} > 0.$$

Equations (7.1) through (7.5) show the impact of changes in the parameters of the model on the equilibrium soil stock at the steady state. The soil stock is an indication of the level of soil conservation, and, hence, comparative static results this section are important in formulating soil conservation policies. As (7.1) suggests, the effect of agricultural output price on the soil stock is indeterminate due to two indeterminate components in the equation ($\frac{\partial \hat{y}}{\partial p^a}$ and $\frac{\partial \hat{y}}{\partial \lambda}$). As mentioned earlier, if the profit motive is higher than the conservation motive, $\frac{\partial \hat{y}}{\partial p^a} < 0$ and if the incremental contribution of cultivation to soil loss dominates that of conservation, $\frac{\partial \hat{y}}{\partial \lambda} > 0$. With these two extra assumptions, first and second components of the (7.1) can be shown to have opposite signs. Thus, even with these rather strong conditions, the effect of agricultural output price change on soil conservation cannot be determined. However, in addition to the above two assumptions, under high enough interest rates, it can be shown that the first part of the equation dominates and that higher prices of agricultural output thereby lead to soil degradation. This result rejects the Barrett's (1991) claim of independence of soil conservation and output price. Thus, higher agricultural prices may promote land degradation only under some special circumstances. LaFrance's (1992) negative and Clarke's (1992) positive output price impacts and on soil conservation are possibilities but they cannot be determined a priori.

Higher agricultural input prices lead to a reduction in land degradation as shown by (7.2). An increase in input prices discourages agricultural production, and the resulting allocation of labour and other resources for soil conservation leads to an increase in the stock of soil. This finding confirms the results of both LaFrance (1992) and Clarke (1992). If there is a subsidy on agricultural inputs, the integrand of equation (3) will be altered as $p^a q(t) - p^I(1-\sigma)x(t) - p^c y(t)$. Thus, the subsidy ($\sigma$) enters the equation linearly but negatively. A reduction in the subsidy on inputs, therefore, is equal to an increase in the agricultural input price. The effect of a reduction in the agricultural input subsidy is thus, represented by equation (7.2). This result suggests that a removal of the agricultural input subsidy under current economic reforms can be viewed as a positive step toward better soil conservation.

The effect of changes in the price of soil conservation is indeterminate (per condition (7.3)). This result contradicts the results of both LaFrance (1992) and Clarke (1992). This result may be due to the immediate negative and subsequent positive impacts of soil conservation on crop yields. Thus, the economic justification of widely applied subsidies for soil conservation is questionable. This indeterminate impact of the price of soil conservation may provide a theoretical explanation for widely reported failures of subsidy programs for soil conservation (see Blaikie, 1985; Pagiola, 1996). A higher discount rate also promotes land degradation as it reduces the value of future cost of soil loss. Finally, higher rate of soil formation reduces land degradation when other things remain unchanged.

In comparison to the previous results, Barrett's (1991) conclusion regarding independence of soil conservation from output and input prices is rejected by the present analysis. The results with respect to the effect of the interest rate and the input prices are similar to those of LaFrance (1992) and Clarke (1992). The price of soil conservation shows a different effect compared to previous results. These differences arise due to changes in model formulation and assumptions regarding the impact of conservation on crop production. According to the results, one cannot predict whether the changes in output price will accelerate or decelerate soil conservation, and the issue finally reduces to an empirical matter. The only policy relevant price effect found in the present analysis is the positive impact of input prices on soil conservation. This finding also has a limited value, however, since it is valid under the strong condition of dominance of marginal impact of cultivation over that of conservation.

CONCLUSIONS AND POLICY IMPLICATIONS

The analysis in this paper combines a dynamic model of soil conservation with a more plausible set of assumptions compared to previous studies to examine the impact of agricultural price policies on soil conservation. As a result, some results are different to those of previous studies. Agricultural output price affects soil conservation, but the direction of the effect cannot be determined a priori. Agricultural input price increase promotes soil conservation, therefore, removal of input subsidies under current economic reforms is a positive step toward better soil management. In contrast to previous results, the effect of price changes in conservation measures is indeterminate. Therefore, policy makers should be cautious in providing subsidies for soil conservation. The results of the present study confirm the previous findings that higher individual time preference promotes soil degradation. Thus, future research should be directed to study the determinants of individual time preference so that the variables that determine the time preference can be manipulated to achieve better conservation levels.

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APPENDICES

Appendix 1. Total differentiation of equations (5.1) and (5.2) applying implicit function theorem result in the following system of equation.

$$\text{(A1)} \qquad A + B \begin{pmatrix} \dfrac{\partial \hat{x}}{\partial p^{a}} & \dfrac{\partial \hat{x}}{\partial p^{I}} & \dfrac{\partial \hat{x}}{\partial p^{c}} & \dfrac{\partial \hat{x}}{\partial \lambda} \\ \dfrac{\partial \hat{y}}{\partial p^{a}} & \dfrac{\partial \hat{y}}{\partial p^{I}} & \dfrac{\partial \hat{y}}{\partial p^{c}} & \dfrac{\partial \hat{y}}{\partial \lambda} \end{pmatrix} = 0$$

Where,

$$A = \begin{pmatrix} q_x & -1 & 0 & -L_x \\ q_y & 0 & -1 & -L_y \end{pmatrix}$$

$$B = \begin{pmatrix} p^a q_{xx} - \lambda L_{xx} & p^a q_{xy} - \lambda L_{xy} \\ p^a q_{xy} - \lambda L_{xy} & p^a q_{yy} - \lambda L_{yy} \end{pmatrix}$$

The determinant of B is;

$$|B| = (p^a q_{xx} - \lambda L_{xx})(p^a q_{yy} - \lambda L_{yy}) - (p^a q_{xy} - \lambda L_{xy})(p^a q_{xy} - \lambda L_{xy}) < 0$$

Since the determinant of B is non zero, the equation 7 can be solved applying Cramer's rule. The results are given below.

(A2.1) $$\frac{\partial \hat{x}}{\partial p^a} = \frac{q_y(p^a q_{xy} - \lambda L_{xy}) - q_x(p^a q_{yy} - \lambda L_{yy})}{|B|} > 0$$

(A2.2) $$\frac{\partial \hat{x}}{\partial p^i} = \frac{(p^a q_{yy} - \lambda L_{yy})}{|B|} < 0$$

(A2.3) $$\frac{\partial \hat{x}}{\partial p^c} = \frac{-(p^a q_{xy} - \lambda L_{xy})}{|B|} > 0$$

(A2.4) $$\frac{\partial \hat{x}}{\partial \lambda} = \frac{L_x(p^a q_{yy} - \lambda L_{yy}) - L_y(p^a q_{xy} - \lambda L_{xy})-)}{|B|} < 0$$

(A2.5) $$\frac{\partial \hat{y}}{\partial p^a} = \frac{q_x(p^a q_{xy} - \lambda L_{xy}) - q_y(p^a q_{xx} - \lambda L_{xx})}{|B|} \lesseqgtr 0$$

(A2.6) $$\frac{\partial \hat{y}}{\partial p^i} = \frac{-(p^a q_{xy} - \lambda L_{xy})}{|B|} > 0$$

(A2.7) $$\frac{\partial \hat{y}}{\partial p^c} = \frac{-(p^a q_{xx} - \lambda L_{xx})}{|B|} < 0$$

(A2.8) $$\frac{\partial \hat{y}}{\partial \lambda} = \frac{L_y(p^a q_{xx} - \lambda L_{xx}) - L_x(p^a q_{xy} - \lambda L_{xy})}{|B|} \lesseqgtr 0$$

(A3.1) $$\frac{\partial \lambda}{\partial p^a} = \frac{q_{ss}[L_x \frac{\partial \hat{x}}{\partial p^a} + L_y \frac{\partial \hat{y}}{\partial p^a}]}{|J|} \lessgtr 0,$$

(A3.2) $$\frac{\partial \lambda}{\partial p^I} = \frac{q_{ss}[L_x \frac{\partial \hat{x}}{\partial p^I} + L_y \frac{\partial \hat{y}}{\partial p^I}]}{|J|} < 0,$$

(A3.3) $$\frac{\partial \lambda}{\partial p^c} = \frac{q_{ss}[L_x \frac{\partial \hat{x}}{\partial p^c} + L_y \frac{\partial \hat{y}}{\partial p^c}]}{|J|} \gtrless 0,$$

(A3.4) $$\frac{\partial \lambda}{\partial r} = 0, \text{ and}$$

(A3.5) $$\frac{\partial \lambda}{\partial K} = \frac{-q_{ss}}{|J|} < 0,$$

Endnotes

i See Ehui *et al.* (1990) for a similar assumption on cross partials that accommodate initial increase of the crop yield due to deforestation and later a decrease in the crop yield due to erosion.

ii Ehui *et al.* (1990) use similar assumption on cross partials in order to make the analysis simple

iii Note that a similar assumption was made by LaFrance (1992) in signing comparative dynamic results.