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**Abstract:** This paper studies farmers who operate in a risky environment at a minimum level of subsistence. In particular is investigated how poverty influence their soil conservation decision in the absence of formal insurance markets. It is shown that the consequences for the soil conservation decision from poverty differ across the agricultural activities considered in the model. Output-induced soil depletion increases with poverty, while soil conservation improves for the same reason when soil conservation inputs and overlapping technologies are considered.

**Keywords:** Farm households, soil fertility.

**JEL classification:** Q12, Q20

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# 1 Introduction

Tropical agriculture is a risky activity. Fragile soils and the high potential capacity of rainfall and wind to cause erosion are special problems. These two factors are important contributors to resource degradation in the Third World. Climatic variability and the occurrence of pests and plagues are in general unpredictable and result in fluctuating incomes. Extreme rainfall variability and other changes in climate tend to be severe in their impact on crop yields and may also lead to natural hazards as droughts and floods.

Another reason for the uncertainty being more pervasive and serious for tropical farmers than for farmers in temperate zones is the lack of well-developed markets. Governmental and private organisations have generally failed to provide insurance markets but also credit markets which may be an important substitute (Binswanger, 1986). In the absence of such markets farmers adopt to risks in various other ways. Household-level strategies as scattering of plots, crop diversification and intercropping are common. These risk management strategies however are seldom able to cope fully with uncertainty.

How farmers are affected by climatic variations may vary widely. Most severe is probably the situation for farmers for whom subsistence is at risk. For this group the outcome of uncertain events can make the difference between survival and starvation. For others, where subsistence is assured because of less climatic variation, more productive soils or larger holdings, costs tend to be less.

The presence of climatic uncertainty raises interesting questions about the behaviour of farmers. In this paper the focus is on how the incentives to arrest land degradation are affected when faced with a stochastic environment and when no formal insurance markets exist. We wish to investigate the relationship between poverty and environmental degradation and in particular, whether farmers whose subsistence is at risk have incentives to deplete their resource base.

Soil conservation issues in uncertain environments have been considered in earlier works. In papers by Pindyck (1984) and Larson (1992) continuous-time control models are applied to analyse optimal decision rules for situations where the state variable changes over time in a stochastic manner. Larson (1992) considers a model where the quality of soil evolves stochastically over time. Pindyck (1984) studies in a similar model the implications of a competitive market equilibrium for renewable resources. Ardila and Innes (1993) analyse for risk averse farmers how production and soil depletion choices are affected when there is uncertainty both in production revenues and end-of-period land price.

The issue of possible links between poverty and resource degradation has increasingly gained attention over the last decade. Many studies mention poverty as an important cause of excessive soil and fertility loss rates observed in the Third World. This is assumed to occur either because poor families lack adequate resources and technology, or because poverty forces them to meet urgent short-term needs, which induce them to "mine" natural capital as soils and forests (see World Bank, 1992; WCED, 1987; Pinstrup-Anderson et al.,1994). More formal studies on such links are Perrings (1989) and Larson and Bromley (1990), who in deterministic dynamic models identify factors creating a situation where resources are degraded. Perrings (1989) develops a model of the open-agrarian economy that operates at a minimum level of subsistence, where resource degradation due to intensified agricultural production is an optimal response to adverse changes. Larson and Bromley (1990) presents a model where the household is assumed to produce under a fallow-rotation system. Their study examines and compares incentives for resource use under private and common property, but also analyses how environmental endowments, a fragile ecosystem and poverty may affect a household's production and degradation incentives. Both studies find that poverty tends to drive up the rate at which soils are deteriorating.

The current study applies a different model to help us understand such mechanisms, where the degradation of land depends not only on the intensity with which land is cultivated, but also on resources devoted to soil conservation measures. It is assumed that peasants have well-defined property rights on a given area of land with an infinite horizon, facing only one source of uncertainty, production risk. I also assume that soil stock at any time can be predicted exactly from current stock level and input use. I then rule out the case where the evolution of the soil stock is stochastic. Furthermore, to limit the number of assets, I follow Larson and Bromley (1990) by assuming no savings market and that households spend all of their income on consumption in every period. This assumption simplifies the analysis substantially and enables us to perform the analysis in a multiperiod setting (infinite horizon) without introducing the analytical complexity of general dynamic stochastic models.

The paper is organised as follows. In the next section a deterministic model of land degradation is presented. In section 3 climatic uncertainty is introduced into the model and it is assumed that if production in any period takes on a value less than a threshold value, the agrarian producers will experience costs in closing the food gap. In section 4, when investigating the relationship between poverty and the incentives for soil conservation, each of the decision variables which affects the evolution of the soil base in the general model is studied in more detail. The last section summarises the findings.

## 2. An economic model of land degradation and soil conservation

Barbier (1990), LaFrance (1992) and Barrett (1996) all consider a decision-maker who has two direct means at his disposal to control fertility loss and/or soil loss[1]. Here we present a model where the land manager has three instruments to influence the soil evolution over time; cultivation intensity, z(t), conservation intensity, c(t), and overlapping technologies, w(t).

Productive inputs may contribute to land degradation in the long run. Fertiliser can accelerate the natural process of soil acidification as nitrates and phosphates leach into the soil profile, while irrigation can raise the table water and lead to soil salinization (see LaFrance, 1992 and the references therein). Cultivation practices and farming techniques are also important for long term soil fertility. The application of more intensive tillage techniques will break up the soil and allow it to be more easily washed away. Repeated tillage and the ploughing up and down the slope instead of along the contour are other examples. Furthermore, extending the crop season and increasing the farm area under cultivation may accelerate the processes of land degradation. Cultivation of land with greater slope and the ploughing of all grassways to increase short-term output will also imply a higher soil loss rate, thus reducing the future productivity of land (McConnel, 1983)[2]. All such actions and inputs are here collapsed into the decision variable, z(t), where a higher value (more intensive cultivation) is assumed to increase immediate production, but decrease long-term soil fertility.

Land degradation can be slowed by a wide range of options, including soil conservation measures such as terraces, drainage ditches, bunds, cut-off drains, and hedgerows. Such structural conservation measures are here represented by the decision variable c(t), and is denoted the intensity of conservation. However, most soil conservation measures are costly in terms of foregone production. Physical structures are found to reduce the effective area by more than 10 percent (Lal, 1987). In addition their construction often moves unproductive soil to the surface, hence affecting immediate output (Lutz, Pagiola and Reiche, 1994). Hence, a higher value of c(t) is assumed to reduce short run output.

A third group of activities considered, is inputs and/or farming practices which when implemented increase both immediate output and long-term soil fertility. Such win-win strategies, w(t), or overlapping technologies in the terminology of Reardon and Vosti (1992), have been ignored in many studies on land degradation and soil conservation. The last years, however, we have witnessed an increasing awareness

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[1] Barbier (1990) and Barrett (1996) focus on the problem of soil erosion. Barbier (1990) considers a productive input package (productive inputs, labour, crop varieties and cropping practices) and a soil conservation package (e.g. bench terraces), while in Barrett (1996) soil depth evolution is a function of cultivation intensity (agricultural practices) and conservation inputs. LaFrance (1992) focuses on the problem of land degradation and considers crop increasing/land degrading inputs (fertilizer, irrigation, ploughing) and soil conserving/crop reducing inputs. Our model is an extension of the model of LaFrance.

[2] A fallow-rotation system can also be interpreted within this framework. More intensive cultivation by leaving less productive land fallow will increase both immediate production and cultivation costs and decrease the future productivity of land.

of such technologies in the literature. Several studies on Africa stress the importance of chemical fertilisers in both arresting soil erosion and increasing short run output (see Brekke et al., 1995; Grepperud, 1996; Alfsen et al., 1995; Aune et al., 1994; Aune and Lal, 1995). The application of fertilisers will provide land with a denser vegetation providing a better protection of soils, thereby preventing water run-off and soil erosion (see Roose, 1977; Logan and Lal, 1990). Reardon and Vosti (1992) mention tied ridges as one important example of an overlapping technology. Another important example is crop residue management including mulching which gives land greater cover and adds nutrients to the soil. A higher value of w(t) is here assumed to increase immediate output and arrest land degradation.

The soil dynamics is described by the following equation

$$\dot{s} = m - n(z_t, c_t, w_t) \qquad \textbf{(1)}$$

where m is a constant representing the natural rate of soil regeneration and $n(z_t, c_t, w_t)$ is the fertility loss function[3]. More intensive cultivation degrades soil fertility, s(t), while more intensive conservation and an increased use of overlapping technologies reduces soil fertility losses[4].

In addition to the three agricultural activities, z(t), c(t), and w(t), the stock of soil fertility, s(t), is also introduced as an argument in the crop production function. Whatever form, land degradation is usually reflected in lower yields. Output for a given crop or crop-mix is then given by the following production function, $f(s_t,z_t,c_t,w_t)$. The production function is twice differentiable and concave in s(t). Higher values of z(t) and w(t) are assumed to increase immediate production, while c(t) is assumed to decrease immediate production since soil conservation measures take up productive land. Furthermore, we assume that the production function is strictly concave in z(t), c(t), and w(t), respectively.

The most important input in third world agriculture, labour, is not explicitly modelled, but is very much connected to the values of z(t), c(t), and w(t). Cropland expansion, seedbed preparation, the adoption of soil conservation measures and mulching are all very labour-intensive activities. As a consequence, the cost function, $h(z_t,c_t,w_t)$, represents not only input unit costs, but also shadow values of non-marketed inputs and the opportunity cost of labour. The cost function is assumed to increase monotonically with each of its arguments, implying that more intensive cultivation, more intensive conservation, and additional use of overlapping technologies all increase a households' costs.

[3] Examples on soil fertility regeneration are nitrogen that enters into the soil organic matter from the decomposition of roots and residues (Ladd and Amato, 1985) and soil formation. Here we follow McConnel (1983), Ardila and Innes (1993) and Barrett (1996) by assuming an autonomous growth in stock.

[4] s(t) is here an index of soil quality or productivity over all the household's land depending on factors such as soil depth, nutrient and mineral content, soil structure and permeability. The single index s(t) limits the number of state variables in our analysis.

The assumptions on technology may be summarised as follows;

$$f_s > 0, f_{ss} \leq 0, f_z > 0, f_{zz} < 0, f_c < 0, f_{cc} < 0, f_w > 0, f_{ww} < 0;$$
$$h_z > 0, h_c > 0, h_w > 0, n_z > 0, n_c < 0, n_w < 0 \qquad (\mathbf{P_1})$$

The objective of the farm household is to maximise the discounted value of an income stream over an infinite horizon, given the equation governing the stock of the soil resource. The households' problem then becomes (time references will in the following be omitted whenever it creates no confusion)

$$\underset{z,c,w}{Max}\ \lambda_0 \int_0^\infty [Pf(s,z,c,w) - h(z,c,w)]e^{-rt} dt \qquad (2)$$

subject to (1), the initial restrictions $s(0)=s_0$, and the control restrictions z(t)≥0, c(t)≥0 and w(t)≥0, where P is the fixed price of the farm output and r the discount factor.

All models of this kind are and must be simplifications of the complex processes determining soil evolution. However, the model captures two essential features of the relationship between land degradation and household behaviour. First, that the choices made by a household have consequences for the resource base. Second, that a farm household faces a series of options lying within their technological horizon, thus there is a continuum of possible actions available to them. The land manager is not necessarily bounded to certain set of activities or practices, but can choose among several strategies or seek a combination of them. In the next section the above model will be analysed within a framework where the outcome of production is uncertain due to climatic variability.

# 3. Soil conservation and farmers for whom subsistence is at risk

Subsistence farmers, for which actual consumption of crops is determined by production, often face a probability of food shortage due to unstable weather. When production is below a level necessary for meeting certain minimal requirements, they experience costs beyond the production loss itself. In the most extreme circumstances these costs are in terms of starvation and malnutrition. For many farmers the consequences may be of less dramatic character. The deficit which arises when their production of crops falls short of the subsistence level can be made up by various resource-demanding activities. The food gap can be closed through collecting, hunting and job search. However, such activities impose large costs in terms of time and neglect of family and farm. Since jobs in the local area are usually seasonal and limited or both, it may be necessary to migrate for a period of time or travel large distances daily[5].

[5] The costs associated with output shortfalls may also be of a different kind. The farmer will during the crop season observe malign climatic conditions and may try to partly compensate for expected production loss by engaging into labour-intensive

In spite of missing insurance markets, some farmers have access to a more informal type of insurance. In the introduction we mentioned self-insurance mechanisms at the household level, but risk management may also be carried out within a wider social group. The existence of solidarity networks in rural areas of the third world, or other informal mechanisms outside of markets, is well documented and provides protection against many sources of risk and minimises the risk of starvation (see Platteau, 1991 and Fafchamps, 1992). However, such institutions are expected to be more effective in a situation with idiosyncratic risk rather than risks of collective nature. This is especially true for areas of homogeneous agroclimates where crop failure due to bad weather tends to affect all adjoining areas, and there are not sufficient resources to prevent all members from sinking below the subsistence level. Mechanisms such as remittances from migrants and food aid may be more effective under these circumstances to alleviate the costs associated with shortfalls[6].

In the following, the above model will be analysed within a framework where subsistence is at risk. In case of shortfalls, farmers are expected to make every possible effort to close the gap and the deficit is made up by cost demanding activities. The following expression represents production net of the costs associated with shortfall

$$Y^* - K(Y^* - Y) \qquad (3)$$

where $Y^*$ is the threshold value assumed constant over time. The critical level may vary across households depending on cultural norms, physiological requirements and family size. If there is a production shortfall ($Y<Y^*$), farmers are assumed to engage in other activities to provide $Y^*$, generating costs depending on the gap, $K(Y^* - Y)$. Here the cost function is assumed linear. This assumption can be relaxed, but affects nothing in the analysis. Expression (3) also enables us to analyse a situation in which a farmer in case of shortfalls has access to an external source of income without any future commitments, $K = 0$. Under this assumption the farmer is fully "insured" in the sense that he at least gets $Y^*$ at no costs regardless of outcome of weather. One example could be remittances from migrated household members.

From (3) it is seen that the minimum subsistence level is related to production (Y) only, and not to net production (Y- h). Such an approach seems reasonable in the context of poor subsistence farmers participating to a lesser extent in market transactions. Most of their production is consumed within the household, and their input use is limited - consisting of seeds from previous crops, simple tools and the

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farming practices aimed at reducing the adverse effects from climatic changes such as water drainage and water retention activities.

[6] Ellsworth and Shapiro (1989) found remittances from migrants to increase during bad times.

households' labour. Input costs in terms of cash expenditures are of relatively minor importance for this group of farmers.

The farm household faces production uncertainty due to climatic variations. The timing and actions in each period are as follows. The farmer makes decisions about farming practices and input use before knowing the outcome of weather. At the end of each period the value of the exogenous shock is realised which again determines the actual net income in that period. It is assumed that production risk is multiplicative, thus the outcome of crop production becomes $f(s,z,c,w)\theta$, where $\{\theta\}$ is a sequence of independent and identically distributed non-negative random variables and $E\theta = 1$. Let $g(\theta)$ be the probability density function of $\theta$, and $G(\theta)$ be the cumulative distribution function for $\theta$ and $\theta \in (\theta_l,\theta_h)$.

The maximisation problem for the household is as follows (for brevity we set P=1[7]);

$$\max_{z,c,w} \ \lambda_0 \int_0^{\infty} \left[ \int_A^{\theta_h} Y\, g(\theta)d\theta + \int_{\theta_l}^{A} ( Y^* - K[Y^* - Y] )\, g(\theta)d\theta - h(z,c,w) \right] e^{-rt}\, dt$$
$$s.t. \quad (1), \ s(0) = s_0 > 0 \ \ and \ \ z(t) \geq 0, \ c(t) \geq 0, w(t) \geq 0 \tag{4}$$
$$where \ \ A \equiv \frac{Y^*}{f(s,z,c,w)} \ \ and \ Y = f(s,z,c,w)\theta$$

The current value Hamiltonian for this problem is

$$H = \lambda_0[f(s,z,c,w)\int_A^{\theta_h} \theta g(\theta)d\theta + Y^* \int_{\theta_l}^{A} g(\theta)d\theta - KY^* \int_{\theta_l}^{A} g(\theta)d\theta + Kf(s,z,c,w)\int_{\theta_l}^{A} \theta g(\theta)d\theta$$
$$- h(z,w,c)] + \lambda\, [m - n(z,w,c)] \tag{5}$$

Using integration by parts, the current value Hamiltonian may be written as

$$H = \lambda_0 [ f(s,z,c,w)(\theta_h - \int_A^{\theta_h} G(\theta)d\theta - K\int_{\theta_l}^{A} G(\theta)d\theta) - h(z,c,w)] + \lambda[m - n(z,c,w)] \tag{6}$$

Given our assumptions ($P_1$), $\lambda_0$=1, and assuming interior solutions, the sufficient conditions for an optimum are (Seierstad and Sydsæter,1987)

[7] Due to the assumption of multiplicative uncertainty, the forthcoming analysis also coincides with analysing output price uncertainty.

$$
\begin{aligned}
H_z &= f_z(s,z,c,w)Q - h_z(z,c,w) \; - \lambda n_z(z,c,w) = 0 \\
H_c &= f_c(s,z,c,w)Q - h_c(z,c,w) \; - \lambda n_c(z,c,w) = 0 \\
H_w &= f_w(s,z,c,w)Q - h_w(z,c,w) - \lambda n_w(z,c,w) = 0 \\
H_s &= r\lambda - \dot{\lambda} = f_s(s,z,c,w)Q, \quad \lim_{t\to\infty} s(t) \geq 0, \quad \lim_{t\to\infty} e^{-rt}\lambda(t) = 0
\end{aligned}
\tag{7}
$$

$$
where \quad Q \equiv \int_A^{\theta_h} \theta g(\theta) d\theta \; + \; K \int_{\theta_l}^{A} \theta g(\theta) d\theta \tag{8}
$$

The first three conditions of (7) describe the optimal paths of the control variables, z, c, and w, respectively. In optimum, the marginal change in production from an increase in each of the agricultural activities multiplied by the term Q, subtracting the marginal change in costs associated with the same increase, is to equal the shadow value of the fertility that is lost (or gained) as a consequence of that increase. The last condition in (7) describes the optimal path of this shadow value.

It should be noted that all optimality conditions depend on the term Q which may be interpreted as a correction term. It is through Q that farmers pay attention to the risk they face. The integrals in (8) are the sum of all outcomes multiplied by their associated probabilities, which matter for a non-shortfall and a shortfall situation, respectively. After substitution Q can be expressed as

$$
Q \equiv 1 - (1-K)G(A)E[\theta | \theta \leq A] \tag{9}
$$

From (9) it follows that Q is a function of both the probability of shortfalls, the costs that goes with this state of nature, and the conditional expectation of θ given a shortfall situation. These are relevant factors for the decision-maker when evaluating the future threat and costs associated with reducing the productivity from land. A marginal increase in the fertility loss rate will imply a lower stock of soil fertility in the future, which again increases the probability of future shortfalls, but also affects the conditional expectation. It also follows from (9) that a marginal reduction in the stock of soil fertility (higher A) will always have an unique effect on Q. The value of Q increases if K>1, while in a situation where a minimum future income is guaranteed, K = 0, Q decreases for a lower stock of soil fertility.

Imposing the stationarity condition $\left(\dot{\lambda} = \dot{s} = 0\right)$ and letting tildes denote steady-state values, implies that the optimality conditions in (7) and (1) must satisfy the follwing four conditions:

$$
\begin{aligned}
f_z(\bar{s},\bar{z},\bar{c},\bar{w}) &= \frac{h_z(\bar{z},\bar{c},\bar{w})}{\tilde{Q}} + \frac{n_z(\bar{z},\bar{c},\bar{w})f_s(\bar{s},\bar{z},\bar{c},\bar{w})}{r} \\
-\frac{n_c(\bar{z},\bar{c},\bar{w})f_s(\bar{s},\bar{z},\bar{c},\bar{w})}{r} &= \frac{h_c(\bar{z},\bar{c},\bar{w})}{\tilde{Q}} - f_c(\bar{s},\bar{z},\bar{c},\bar{w}) \\
f_w(\bar{s},\bar{z},\bar{c},\bar{w}) - \frac{n_w(\bar{z},\bar{c},\bar{w})f_s(\bar{s},\bar{z},\bar{c},\bar{w})}{r} &= \frac{h_w(\bar{z},\bar{c},\bar{w})}{\tilde{Q}} \\
m &= n(\bar{z},\bar{c},\bar{w})
\end{aligned} \qquad \textbf{(10)}
$$

The left-hand side of each condition is now the marginal benefit associated with increasing an activity, while the right-hand sides of each condition reflects all marginal costs associated with the same increase. Our rewriting of the dynamic system, has allowed for the correction term, Q, to occur in one term only, the input cost term.

If the farmer operates at a level where the minimum subsistence level is never threatened, in the model interpreted as a situation where the probability of shortfalls in the steady state, G(A)=0, Q will equal one. Under this assumption it is seen from (10) that the optimal fertility loss decision is unaffected by climatic uncertainty. If however the farmer faces a positive probability of shortfalls, independent of whether some kind of assistance is provided or not, the correction term Q will be different from 1. As a consequence the optimal path of fertility losses will be affected by the presence of climatic uncertainty, in spite of the risk neutral preferences assumed in this model.

It follows from (10 ) that the effect on the optimal stock of soil fertility, for Q different from 1, can be analysed as a shift in the cost function in a deterministic version of our model. However, to derive the saddle path condition for a dynamic system consisting of three decision variables is a tedious and analytically complex task. In the following we choose to study each decision variable at a time (three partial models) rather than the general model, when analysing the effect from poverty on the optimal stock of soil fertility. This approach simplifies the analysis substantially, derives key points more rapidly, and illuminates key differences between the three agricultural activities, thus creating a better understanding of the various forces at play. However, the saddle path condition and comparative statics for the general model is presented in Appendix A and B, respectively.

## 4. The role of each agricultural activity

By keeping conservation intensity, $c_t = \underline{c}$, and overlapping technologies, $w_t = \underline{w}$, fixed at some level throughout the planning horizon a unique functional relationship between fertility loss ($X_t$) and cultivation intensity ( $z_t$) is obtained. By inverting $X_t = n(z_t, \underline{c}, \underline{w})$ w.r.t. $z_t$, cultivation intensity becomes a function of the fertility loss rate;

$$z_t = n^{-1}(X_t, \underline{c}, \underline{w}) = Z(X_t) \tag{11}$$

By inserting (11) into both the production function and the cost function presented in the above section, the following partial model is derived, hereafter denoted the Cultivation model

$$\underset{X_t}{Max} \int_0^{\infty} [F(S_t, X_t) - C(X_t)] e^{-rt} dt \tag{12}$$

$$s.t.\ \dot{S} = M - X_t \tag{13}$$

where S now denotes the stock of soil fertility, and M the soil regeneration rate. The technological properties that follow from $P_1$ for this model are,

$F_S>0$, $F_{SS}<0$, $F_X>0$, $C_X>0$. **($P_2$)**

Similar procedures as above, now keeping $z_t$ and $w_t$, and $z_t$ and $c_t$, fixed at some level, yield two additional partial models which will be denoted the Conservation model and the Win-win model, respectively. As was the case for the Cultivation model, these two models may also be represented by maximisation problem (12)-(13)[8]. The technology properties which follow from $P_1$ for the Conservation model ($P_3$) and for the Win-win model ($P_4$,) are as follows,

$F_S>0$, $F_{SS}<0$, $F_X>0$, $C_X<0$. **($P_3$)**

$F_S>0$, $F_{SS}<0$, $F_X<0$, $C_X<0$. **($P_4$)**

We thus have three different models, each focusing on one side of a farmers' input and farming practice decisions. In all models, inputs and farming practices are suppressed so that fertility loss ($X_t$) has become the decision variable. By comparing $P_2$, $P_3$ and $P_4$ it is noted that the assumptions on the cost function vary across the models. In the Cultivation model the costs increase with $X_t$, since higher fertility loss rates imply that more resources are devoted to cultivation activities. In the Conservation model

[8] For notational convenience, the notation is kept similar for the three models throughout the paper.

and the Win-win model on the other hand, costs decrease with a higher fertility loss rate. Here, a higher fertility loss rate means less resources devoted to soil conservation and overlapping technologies, respectively.

The assumptions on the production function also vary across the three partial models. For the Cultivation model, a higher fertility loss rate increases immediate production due to more intensive cultivation. For the Conservation model, the same relationship apply but for a different reason; a higher fertility loss rate now means less resources devoted to soil conservation, so that less productive land is set aside for conservation practices. In the Win-win model, output decreases with higher fertility losses since less fertility enhancing inputs are applied.

Applying the same procedures as in the previous section, assuming that the current value Hamiltonian (V) for problem (12)-(13) is strictly concave in $X_t$ and concave in $S_t$, $\lambda_0=1$, and assuming interior solutions, the sufficient conditions for optimum are (Seierstad and Sydsæter, 1987) (time references are in the following omitted)

$$V_X = F_X(S,X)W - C_X(X) - \lambda = 0, \qquad \lim_{t\to\infty} S(t) \geq 0 \tag{14}$$

$$V_S = r\lambda - \dot{\lambda} = F_S(S,X)W, \qquad \lim_{t\to\infty} e^{-rt}\lambda(t) = 0 \tag{15}$$

$$\text{where } W \equiv 1 - (1-K)G(A)E[\theta \mid \theta \leq A], \quad \text{and} \quad A \equiv \frac{Y^*}{F(S,X)} \tag{16}$$

If we turn to the steady-state analysis (see App.C for saddle path equilibrium conditions), letting bars denote the steady state equilibrium values, the optimality conditions ((14) and (15)) may be expressed in the following way;

$$F_X(\bar{S},M) - \frac{C_X(M)}{\overline{W}} = \frac{1}{r}F_S(\bar{S},M) \tag{17}$$

The reference case where G(A)=0 implying that $\overline{W}$ equals one, will in the following be denoted $\bar{S}_1$. This situation, where the optimal soil conservation decision is unaffected by climatic uncertainty, is already discussed in the section 3. The following expression may be derived from changes in the cost function ($\beta$)[9]

[9] Where the constant $\beta$ is multiplied to the cost function (and W set equal to one) in order to analyse the effect from poverty on the optimal soil conservation decision.

$$\frac{d\bar{S}}{d\beta} = -\frac{C_X(M)}{D_2} \qquad \begin{cases} >0 & if \quad C_X(M) < 0 \\ <0 & if \quad C_X(M) > 0 \end{cases} \tag{18}$$

where $D_2 > 0$ is shown to be required for a saddle path equilibrium (see App.C).

Let us first consider the Cultivation model where $C_X>0$ for the group of farmers facing the most severe burden of poverty. Here, subsistence is at risk, $G(A)>0$, and no guaranteed future minimum income is assured, $K>1$. Under these assumptions $\overline{W}$ is always larger than 1. The marginal cost associated with more intensive cultivation is now lower than is the situation for the reference case. As a consequence the incentives for soil conservation have weakened. The optimal steady state stock of soil fertility under this assumption, $S = \overline{S}_2$, will now be lower than $\overline{S}_1$. A farmer operating at the minimum subsistence level tends to exploit the soil more than a farmer for which subsistence is never threatened. The farmer finds it optimal to harvest more soil in spite of the future decrease in expected production that arise from such a behaviour.

Increasing levels of poverty can be interpreted as an increasing probability of shortfall, higher costs associated with shortfalls, a relatively higher threshold level and higher discount factor. All these factors describe an environment where the variability in climate is severe, where there are few opportunities of alternative sources of income in case of shortfalls, and where the household size is relatively large compared to endowments. The incentives for soil-depletion increase with a higher level of these factors (see App.C.4-6). Poverty forces the farmer to pay less attention to future benefits that arise from soil conservation. Farmers are securing their short-term needs at the expense of long-term needs. The strategy for survival imply resource degradation in this model.

Consider now the same model for farmers which are better off. Now the farmer is assumed to be fully "insured" in the sense that there are no costs associated with closing the food gap, $K = 0$. The farmer is guaranteed a future minimum income equal to the threshold value. Under this assumption, the correction term $\overline{W}$ equals $1-G(A)E(\theta|\theta<A)$. As long as the probability of shortfalls is positive, $\overline{W}$ is less than 1. As a consequence, the cost term in (17) is now inflated compared to the reference case. Hence, the results are opposite of the ones arrived at for the "uninsured" farmer. The optimal stock of steady state soil fertility $S = \overline{S}_3$ will be higher than $\overline{S}_1$. The incentives for soil conservation have improved, not because the farmer has become more aware of the land degradation problem, but because the guarantee of a future minimum income reduces the incentives to work hard, to apply more effort and inputs into crop production, and as a by-product fertility loss rates are lower over time. Access to reliable future assistance in terms of food aid or remittances from migrating household members tends to improve the

incentives for soil conservation in this model. The results for the Cultivation model may be summarised as follows; $\overline{S}_3 > \overline{S}_1 > \overline{S}_2$.

Let us now turn to the Conservation model to study the consequences of poverty. Since the first derivative of the cost function with respect to the fertility loss rate is negative rather than positive as was the case for the Cultivation model, all conclusions will be opposite; $\overline{S}_2 > \overline{S}_1 > \overline{S}_3$. The optimal stock of soil fertility in steady state for a "uninsured" farmer where subsistence is at risk, $\overline{S}_2$, is higher than the optimal steady state soil fertility for a farmer not operating close to the minimum subsistence level, $\overline{S}_1$. Both increases in the costs associated with shortfalls and in the threshold value, now improve the incentives for soil conservation. The only course of action whose effect remains unchanged compared to the Cultivation model is the one from higher discount rates[10]. The threat and costs of shortfalls in this model induce the farmer to increase his effort into soil conservation activities. The need to avoid starvation acts here as an incentive to improved soil conservation. The strategy for survival now does not imply resource degradation, but a improved long-term resource management.

A fully "insured" farmer will also behave opposite of what was the situation in the Cultivation model. The optimal stock of soil fertility in steady state, $\overline{S}_3$, is lower than the fertility stock for the reference case, $\overline{S}_1$. The incentives for soil conservation have worsened since the decision maker no longer experiences all future costs associated with soil depletion. The harvesting of soil in a given time period will only yield a production loss in those future periods where production exceeds the threshold value. In case of shortfall the farmer will receive $Y=Y^*$ independent of his past resource management decisions. As for the Cultivation model, an "insurance" provides less incentives to apply inputs, which in this model means less resources devoted to conservation measures. Hence, the fertility loss rate will be higher over time.

The conclusions from the Win-win model are equal to the ones for the Conservation model since the first derivative of the cost function is negative for both models. Poor farmers will increase the use of overlapping technologies compared to the reference case, while an «insured» farmer will reduce the amount of resources devoted to this activity ($\overline{S}_2 > \overline{S}_1 > \overline{S}_3$).

In the Cultivation model the farmer faces a trade-off between expected immediate production and expected future production. As a consequence, the farmer gives priority to short-term benefits at the

[10] The effect on the stock of soil fertility from an increase in the discount rate within a general framework (two or more control variables) is analysed by LaFrance (1992), Barrett (1996) and Grepperud (1996). Although the effect in principle can go either way, smooth functional forms will in general yield a lower steady state fertility stock (Grepperud, 1996). It may be shown that the same conclusion will apply for the general model presented in this paper.

expense of long-term benefits when "insurance" is absent. In this model it will always be preferable for the farmer to delay the costs associated with shortfalls, by conducting intensive cultivation today. Here, resource degradation is an optimal response to an adverse environment.

When soil conservation inputs and overlapping technologies are considered, the same adverse environment becomes an incentive for improved resource management. The trade-off between expected immediate production and expected future production are absent in these models. In fact, the farmer can increase the expected long-term production without any decrease in expected short-term production, if overlapping technologies are considered. The option of using such measures means that the farmer has access to a long term self-insurance device, which enable him to «maximise» the number of periods in which minimum subsistence needs are fulfilled. For the Cultivation model however, this device is not present. It is the lack of opportunities which forces the farmer to behave myopically in this model.

If all activities are analysed simultaneously it is not possible to arrive at unique conclusions (see App. B). There are two main reasons for this conclusion. First, because in a general model several indirect effects via both the production function, the cost function and the soil loss function, are introduced, represented by cross partial derivatives of the same functions. To my knowledge the empirical literature on soils do not provide complete information on such relationships. Even if reasonable assumptions are made there are still effects which will work in opposition to each other, and the restrictive assumption of all cross partial derivatives being equal to zero, does not either help us to sign the optimal soil conservation decision. This brings us to the second reason. The partial direct effect from poverty (via cultivation intensity) on optimal stock of soil fertility opposes the same effect on the optimal stock of soil fertility when conservation intensity and overlapping technologies are considered. In order to determine the sign of the total effect additional assumptions on technology are needed. Thus it remains unclear whether poverty in this model induces farmers to manage their resources poorly in the long run. The theoretical analysis suggests that poverty may affect soil conservation decisions in various ways, but the total effect is indeterminate.

Perrings (1989) and Larson and Bromley (1990) find that poverty leads to land degradation. The reason for their finding is that their models, similar to the Cultivation model, assume resource depletion to be production-driven. Perrings assumes that higher activity levels means greater intensity of labour and more resource depletion. Larson and Bromley study a fallow-rotation system where higher agricultural production means less area under fallow, hence giving soil less time to regenerate. The only option for the resource manager seeking to conserve soil is to abstain from some production. Neither analysis considers the possibility of controlling erosion by planting trees as windshields, constructing terraces, building waterways, drainage systems and by overlapping technologies. The existence of such measures means that there are several and often opposite forces at play both in connection with poverty-related factors.

Perrings (1989) shows how economies under certain conditions may evolve along an optimal path of extinction. Such results could well arise in this analysis too. The partial models are for simplistic reasons analysed in steady state. As a consequence the optimal fertility loss rate will equal the natural rate of soil fertility regeneration. However, it is easy to identify conditions under which a steady state equilibrium is no longer attainable for the farmer, meaning the stock of soil fertility is declining over time. All factors which reduce the optimal stock of soil fertility in a steady state may under certain conditions induce a rational farmer to mine the soil. For the Cultivation model, such factors are poverty-related; where subsistence is highly at risk, and shortfalls are associated with high costs. For the Conservation model and the Win-win model, factors which contribute to high costs in arresting the degradation of land (high input costs), make an optimal path towards extinction more likely. Fragile soil is one obvious candidate. Soils which posses different physical and chemical properties that make them less resistant to soil erosion means more resources are needed to keep the soil loss rate low. Both access to technology and each farmer's ability to practice effective soil conservation is also crucial. To conclude, a continuing degradation process of the resource base may very well be part of an optimal strategy for farmers due to unfavourable climatic conditions, erosion-prone soils or limited access to soil conservation technology, however some of these factors could induce the farmer to reduce the speed at which land is exploited.

The analysis is done under the assumption of no market for savings. This assumption may be empirically plausible in view of the fact that such markets are generally missing or incomplete in the poor rural areas of the Third World, limiting the role of financial assets. However, savings in real assets are more common, and individual wealth accumulation can take various forms such as food-storage, livestock and jewellery. In addition both inputs (bullocks and land) and consumption itself (durable consumption goods) may also act as sources of insurance against risk since such assets can be depleted in case of crop failure, hence enabling the farmer to better cope with climatic and production fluctuations.

However, extensive stock piling in order to eliminate the possibility of future shortfalls is not realistic since there are often costs (storage costs and depreciation costs) associated with such activity. In many cases the stock itself is also vulnerable to climatic changes. Examples here are food-storage and livestock. There is also a positive probability for a sequence of bad outcomes, which if it occurs, forces the farmer to rapidly deplete his stock of real assets. As long as stock piling remains an expensive activity, the farmer is not able to cope fully with the problem of climatic uncertainty, and his optimal soil conservation decision will be affected. However, the option of stock piling is likely to dampen the impact on land degradation from poverty identified in each of the partial models.

## 5. Conclusion

This paper studies farmers who operate in a risky environment and how poverty influences their soil conservation decisions in the absence of formal insurance markets. In particular, the analysis considers farmers which operate close to or at a minimum level of subsistence. Here, farmers are assumed to experience costs in order to close the food gap in case of shortfalls. These costs are internalised into their net benefit function from engaging in agricultural production activities. A situation in which the farmer is assured a minimum future income in case of shortfalls is also considered.

Socially excessive soil depletion has been blamed on external effects from soil erosion, on short planning horizons, and on high farmer discount rates. This analysis finds that both poverty and the existence of informal insurance schemes for farmers operating close to their subsistence requirements may have the same effect. As long as farmers are exposed to a positive probability of shortfalls deviations from the social optimal fertility loss path is observed, because of the costs that go with shortfalls. This matter despite the assumption of risk neutral preferences applied in this analysis.

Three partial models are introduced, each describing one important side of the production behaviour of third world farmers. One important result is the identification of contradicting effects across the partial models. The role of the costs associated with soil conservation is the fundamental reason for the diverging conclusions arrived at in the three partial models. In the Cultivation model, a farmer operating at or close to the subsistence minimum will deplete the soil more than a farmer for whom subsistence is never threatened. This model has similarities with Ardila and Innes (1993), Perrings (1989) and Larson and Bromley (1990) in that soil depletion is output-induced. For the Conservation model the effect on the soil conservation incentives is exactly the opposite. The threat of shortfalls induces the farmer in this model to invest more resources in soil conservation. The same conclusion matter for overlapping technologies.

The results show that the role of poverty in relation to land degradation is complex and that there are forces at play which work in different directions. Poverty is not necessarily a unidirectional causal factor to environmental degradation. To be able to predict the effect of poverty on resource management decisions, substantial empirical evidence is needed, particular on farming practices and input-use and how their application affects the productivity of the soil asset. The analysis further stresses the importance of knowledge and the access to effective soil conservation inputs. The knowledge and presence of such devices can offset malign consequences of poverty and risk in tropical agriculture and serve as an instrument for long-term self-insurance behaviour. Soil conservation inputs and overlapping technologies, in contrast to productive inputs, allow farmers to take action to secure both immediate and future consumption needs.

Barbier (1990), LaFrance (1992) and Barrett (1996) as well as this study assume soil conservation efforts to be effective only in the time period in which they are implemented. Grepperud (1996), in contrast, presents a model where soil conservation measures have lasting effects on the soil base. Such an approach seems to cover central features of many important conservation measures like terraces, bunds, ditches and windbreaks. However, Grepperud (1996) finds that the main properties remain unchanged independent of whether soil conservation measures are analysed as time-limited inputs or as conservation capital. What is important, and separates them from productive inputs, is that additional resources are needed to combat soil degradation processes. As a consequence all conclusions arrived at in this analysis will prevail if analysing conservation measures as the build-up of conservation capital rather than conservation inputs.

Another conclusion is that if effective insurance markets are not available, and farmers therefore have to self-insure, one means by which they can do this is through soil conservation measures and overlapping technologies. However, insurance and social security reforms could not be expected neither to increase or decrease soil conservation.

For many regions of the Third World, soil conservation activities such as terracing have been a traditional part of farming practice. For other regions, fallow-cultivation systems are practised. In such traditional farming systems, soil fertility is maintained by returning cropland to fallowland for a shorter or longer period of time. More intensive cultivation under this system means less land under fallow (less soil conservation) and consequently higher fertility losses. The Cultivation model seems to capture the essential features by which such indigenous farming systems can be characterised. The theoretical analysis suggests that for fallow-cultivation systems poverty-associated factors tend to strengthen the incentives for soil-depletion. As a consequence the role of governments may be important in such areas in informing and encouraging the application of other soil conservation measures, in order to prevent poor resource management.

# Appendix A:

## Necessary and sufficient conditions for a local saddle path equilibrium for problem (4).

In section 3 we showed that the effect from poverty and «insurance» (Q different from 1) on the soil conservation incentives can be interpreted as a shift in the cost function of a deterministic version of the model presented in (4). We multilpy the cost function in the deterministic version of the model with a constant $\beta$, thus the maximisation problem for the household becomes;

$$\begin{aligned} &\underset{z,c,w}{Max} \quad \lambda_0 \int_0^{\infty} [f(s,z,c,w) - \beta h(z,c,w)] e^{-rt} dt \\ &s.t. \quad \dot{s} = m - n(z,c,w) \end{aligned} \qquad \text{A.1}$$

The current value Hamiltonian for this problem is

$$H = f(s,z,c,w) - \beta h(z,c,w) + \lambda[m - n(z,c,w)] \qquad \text{A.2}$$

The optimality conditions for problem A.1 given that the current value Hamiltonian is strictly concave in z,c, and w, respectively, concave in s, $\lambda_0=1$, and given the tranversality conditions presented in (7), are as follows:

$$H_z = f_z(s,z,c,w) - \beta h_z(z,c,w) - \lambda n_z(z,c,w) = 0 \qquad \text{A.3}$$
$$H_c = f_c(s,z,c,w) - \beta h_c(z,c,w) - \lambda n_c(z,c,w) = 0 \qquad \text{A.4}$$
$$H_w = f_w(s,z,c,w) - \beta h_w(z,c,w) - \lambda n_w(z,c,w) = 0 \qquad \text{A.5}$$
$$H_s = f_s(s,z,c,w) = r\lambda - \dot{\lambda} \qquad \text{A.6}$$
$$\dot{s} = m - n(z,c,w) \qquad \text{A.7}$$

One way to derive the saddle path condition for the dynamical system A.3-7 is to solve the system A.3-5 for z, c, and w, simultanously. Hence we arrive at the following three equations

$$z = A(s,\lambda,\beta) \qquad \text{A.8}$$
$$c = B(s,\lambda,\beta) \qquad \text{A.9}$$
$$w = E(s,\lambda,\beta) \qquad \text{A.10}$$

By inserting A.8, A.9 and A.10 into A.6 and A.7, respectively, we arrive at a dynamic system for which the saddle path condition may be derived. We find that the eigen values that correspond to this system (evaluated in equilibrium) are real and opposite, if

$$J = \begin{vmatrix} -[n_z A_s + n_c B_s + n_w E_\lambda] & -[n_z A_\lambda + n_c B_\lambda + n_w D_\lambda] \\ & \\ -[f_{ss} + f_{sz} A_s + f_{sc} B_s + f_{sw} E_s] & [r - f_{sz} A_\lambda - f_{sc} B_\lambda] - f_{sw} D_\lambda \end{vmatrix} < 0 \qquad \text{A.11}$$

Hence the equilibrium is a saddle path if

$$\begin{aligned} J = & -n_z[A_s(r - f_{sc}B_\lambda - f_{sw}E_\lambda) + A_\lambda(f_{ss} + f_{sc}B_s + f_{sw}E_s)] \\ & -n_c[B_s(r - f_{sz}A_\lambda - f_{sw}E_\lambda) + B_\lambda(f_{ss} + f_{sz}A_s + f_{sw}E_s)] \\ & -n_w[E_s(r - f_{sz}A_\lambda - f_{sc}B_\lambda) + E_\lambda(f_{ss} + f_{sz}A_s + f_{sc}B_s)] \quad < 0 \end{aligned} \qquad \text{A.12}$$

Where

$$A_s = \frac{1}{F}[-f_{zs}(H_{cc}H_{ww} - H_{cw}H_{wc}) + H_{zc}(f_{cs}H_{ww} - H_{cw}f_{ws}) - H_{zw}(f_{cs}H_{wc} - H_{cc}f_{ws})]$$

$$A_\lambda = \frac{1}{F}[n_z(H_{cc}H_{ww} - H_{cw}H_{wc}) + H_{zc}(n_w H_{cw} - n_c H_{ww}) - H_{zw}(n_w H_{cc} - n_c H_{wc})]$$

$$A_\beta = \frac{1}{F}[h_z(H_{cc}H_{ww} - H_{cw}H_{wc}) + h_c(h_w H_{cw} - h_c H_{ww}) + H_{zw}(h_c H_{wc} - h_w H_{cc})]$$

$$B_s = \frac{1}{F}[H_{zz}(n_c H_{ww} + n_w H_{cw}) + n_z(H_{cz}H_{ww} - H_{cw}H_{wz}) + H_{zw}(n_w H_{cz} - n_c H_{wz})]$$

$$B_\lambda = \frac{1}{F}[H_{zz}(h_c H_{ww} + h_w H_{cw}) + h_z(H_{cz}H_{ww} - H_{cw}H_{wz}) + H_{zw}(h_w H_{cz} - h_c H_{wz})]$$

$$B_\beta = \frac{1}{F}[H_{zz}(h_c H_{ww} + h_w H_{cw}) + h_z(H_{cz}H_{ww} - H_{cw}H_{wz}) + H_{zw}(h_w H_{cz} - h_c H_{wz})]$$

$$E_s = -\frac{1}{F}[H_{zz}(f_{ws}H_{cc} + f_{cs}H_{wc}) + H_{zc}(f_{cs}H_{wz} - f_{ws}H_{cz}) + f_{zs}(H_{cz}H_{wc} - H_{cc}H_{wz})]$$

$$E_\lambda = \frac{1}{F}[H_{zz}(n_w H_{cc} - n_c H_{wc}) - H_{zc}(n_w H_{cz} - n_c H_{wz}) + n_z(H_{cz}H_{wc} - H_{wz}H_{cc})]$$

$$E_\beta = \frac{1}{F}[H_{zz}(h_w H_{cc} - h_c H_{wc}) - H_{zc}(h_w H_{cz} - h_c H_{wz}) + h_z(H_{cz}H_{wc} - H_{wz}H_{cc})]$$

$$\text{and} \quad F = H_{zz}(H_{cc}H_{ww} - H_{cw}H_{wc}) - H_{zc}(H_{cz}H_{ww} - H_{cw}H_{wz}) + H_{zw}(H_{cz}H_{wc} - H_{cc}H_{wz})$$

After extensive manipulation A.12 may be rewritten as follows

$$J = \frac{r}{F}D < 0$$

A.13

*where*

$$D = n_z\left[R_{zs}(R_{cc}R_{ww} - R_{cw}R_{wc}) - R_{zc}(R_{cs}R_{ww} - R_{cw}R_{ws}) + R_{zw}(R_{cs}R_{wc} - R_{cc}R_{ws})\right] \qquad \text{A.14}$$
$$- n_c\left[R_{zs}(R_{cz}R_{ww} - R_{cw}R_{wz}) - R_{zz}(R_{cs}R_{ww} - R_{cw}R_{ws}) + R_{zw}(R_{cs}R_{wz} - R_{cz}R_{ws})\right]$$
$$+ n_w\left[R_{zs}(R_{cz}R_{wz} - R_{cc}R_{wz}) - R_{zz}(R_{cs}R_{wc} - R_{cc}R_{ws}) + R_{zc}(R_{cs}R_{wz} - R_{cz}R_{ws})\right]$$

and

$$R_{zz} = H_{zz} - \frac{n_z f_{sz}}{r}$$
$$R_{cc} = H_{cc} - \frac{n_c f_{sc}}{r}$$
$$R_{ww} = H_{ww} - \frac{n_w f_{sw}}{r}$$
$$R_{zs} = H_{zs} - \frac{n_z f_{ss}}{r}$$
$$R_{zw} = H_{zw} - \frac{n_z f_{sw}}{r}$$
$$R_{cs} = H_{cs} - \frac{n_c f_{ss}}{r}$$
$$R_{cz} = H_{cz} - \frac{n_c f_{sz}}{r}$$
$$R_{ws} = H_{ws} - \frac{n_w f_{ss}}{r}$$
$$R_{zc} = H_{zc} - \frac{n_z f_{sc}}{r}$$
$$R_{cw} = H_{cw} - \frac{n_c f_{sw}}{r}$$
$$R_{wc} = H_{wc} - \frac{n_w f_{sc}}{r}$$
$$R_{wz} = H_{wz} - \frac{n_w f_{sz}}{r}$$

If the Hamiltonian is assumed to be strictly concave in (z,c,w) then F <0. For the saddle path condition to be fulfilled this imply that D >0.

## Appendix B:

### Comparative statics. The effect of poverty on steady state soil fertility.

We want to investigate how a Q different from 1 affects the optimal soil conservation decision. Imposing the stationary conditions on the problem presented in Appendix A and differentiating the dynamic system w.r.t s, z, c,w, and β, yields, after some tedious algebra, the following expression for the impact on steady state soil fertility for a change in β;

$$\frac{d\bar{s}}{d\beta} = \frac{1}{D}\{\, n_z[h_z(R_{cc}R_{ww} - R_{cw}R_{wc}) - R_{zc}(h_cR_{ww} - h_wR_{cw}) + R_{zw}(h_wR_{cc} - h_cR_{wc})]$$

$$- n_c[h_z(R_{cz}R_{ww} - R_{cw}R_{wz}) - R_{zz}(h_cR_{ww} - h_wR_{cw}) + R_{zw}(h_cR_{wz} - h_wR_{cz})] \qquad \text{B.1}$$

$$+ n_w[h_z(R_{cz}R_{wc} - R_{cc}R_{wz}) - R_{zz}(h_cR_{wc} - h_wR_{cc}) + R_{zc}(h_cR_{wz} - h_wR_{cz})]\,\}$$

All R - terms are defined in Appendix A and we know from the saddle path condition that D >0 (see App.A).

Applying $P_1$ does not enable us to sign any of R-terms present in the numerator of B.1. If further assumptions are made, particularly on the cross partial derivatives of the production function, some of the R-terms become determinate. However, signing all R-terms is not a sufficient condition for reaching a determinant conclusion w.r.t the effect of poverty on steady state soil fertility. We are still left with opposing effects in the numerator of B.1. A simplifying assumption is to set all indirect effects equal to zero (all partial cross derivatives of the production function, the cost function and the fertility loss function are negligible). Under these assumptions all R-terms with the exception of three, become zero. The numerator of B.1 can now be written as follows

$$n_zh_zR_{cc}R_{ww} + n_ch_cR_{zz}R_{ww} + n_wh_wR_{zz}R_{cc} \qquad \text{B.2}$$

It follows from B.2 that, under the assumptions made, the first term is positive while the next two terms are negative, since $R_{cc}=H_{cc}<0$ $R_{ww}=H_{ww}<0$ and $R_{zz}=H_{zz}<0$. Thus we have identified three direct effects which oppose each other in determining the sign of the effect from poverty on the optimal soil conservation decision. For an explanation of each of these direct effects see section 4.

# Appendix C

## Necessary and sufficient conditions for a local saddle path equilibrium for problem (12-13)

By differentiating (14) w.r.t time and inserting (15), yields an expression for dX/dt which together with (13) define a dynamic system. Under the assumption of all third derivatives being zero, the eigen values that correspond to this system (evaluated in equilibrium) are real and opposite, if

$$\begin{vmatrix} \dfrac{rV_{xx} - V_{sx}}{V_{xx}} & -1 \\ \dfrac{rV_{sx} - V_{ss}}{V_{xx}} & 0 \end{vmatrix} < 0 \qquad \text{C.1}$$

Hence the equilibrium is a saddle point if

$$\frac{rV_{SX} - V_{SS}}{V_{XX}} < 0 \qquad \text{C.2}$$

Since the current value Hamiltonian is assumed strictly concave in X, and concave in S, the following condition must be fulfilled

$$D_2 \equiv V_{SX} - (1/r)V_{SS} > 0 \qquad \text{C.3}$$

Differentiating (17) with respect to $\overline{S}$, r, K and Y*

$$\frac{\partial \overline{S}}{\partial r} = -\frac{F_S(\overline{S}, M)\overline{W}}{r^2 D_2} < 0 \qquad \text{C.4}$$

$$\frac{\partial \overline{S}}{\partial K} = \frac{-C_X(M)G(A)}{\overline{W}\ D_2} \begin{cases} > 0 & if \quad C_x < 0 \\ < 0 & if \quad C_x > 0 \end{cases} \qquad \text{C.5}$$

$$\frac{\partial \overline{S}}{\partial Y^*} = \frac{C_X(M)(1-K)g(A)}{\overline{W}D_2} \begin{cases} > 0 \text{ if } C_X > 0 \text{ and } K = 0, & or\ C_X < 0 \text{ and } K > 1 \\ < 0 \text{ if } C_X > 0 \text{ and } K > 1, & or\ C_X < 0 \text{ and } K = 0 \end{cases} \qquad \text{C.6}$$

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