CHAPTER IV

STUDY APPROACH TO MODELING THE DYNAMICS OF OPTIMAL SOIL FERTILITY MANAGEMENT IN MALAWI

As already pointed out, this study used a dynamic optimisation approach to derive and analyse the optimal conditions for soil resource extraction and use in Malawi. This chapter presents the analytical framework, derives and discusses analytical results for the optimal control model of the soil-mining problem under study.

4.1 The Analytical Framework and The Optimal Control Approach

In order to properly analyse optimality of soil resource use over time, it is important to first understand the nature of the soil degradation problem. Soil is often classified as a slowly renewable resource and can thus be treated as both renewable and exhaustible resource (Barbier, 1986). For example, when the major reason for soil degradation is the depletion of soil nutrients' stock (soil mining), soil quality can be replenished through the natural growth of the soil augmented by the application of external inputs such as inorganic fertilisers or manure. Soil mining can, therefore, occur and drastically affect land productivity without posing an irreversible long-run threat to land productivity since measures are available to compensate for nutrient losses (Brekke et al., 1999). Soil physical structure on the other hand, can be considered as an exhaustible resource. Over a reasonable time horizon, erosion induced losses of topsoil and damage to soil physical structures are thus irreversible. Although soil nutrient depletion can be countered by application of external inputs, soil mining (nutrient depletion) remains the major limitation to crop productivity in Malawi. Nutrient depletion is the main form of soil degradation in Malawi because the insufficient application of external inputs (e.g., chemical and organic fertilisers) among smallholder farmers cannot compensate nutrient losses due to crop harvest and nutrient lost through erosion of the topsoil. The present study, therefore, focuses on soil quality as measured in terms of soil nutrient stock and considers depletion of soil nutrients' stock to mainly be through erosion of topsoil and nutrient extraction through crop harvest.

The fact that a significant propotion of land in farming and most forested areas in the third world are managed under various forms of common property regimes and, sometimes, public property has been emphasised as a source of resource overexploitation (Glantz, 1977; Allen, 1985; Sinn, 1988; Perrings, 1989; Lopez and Niklitschek, 1991). Perman et al. (1999) indicates that the title "common property resource" is used whenever some customary procedures govern use of the resource in question. Feder et al. (1988) have empirically documented the negative effects of insecure land tenure property rights on agriculture productivity. However, various authors have argued that traditional communities develop communal management systems that control access to and use of resources that induce a socially efficient exploitation (Dasgupta and Maler, 1990; Larson and Bromley, 1990). In other words, traditional systems would internalise the potential externalities arising from of lack of individual resource ownership.

Smallholder agricultural land in Malawi is exclusively under customary tenure system. Under this system, land belongs to the government and traditional chiefs are the appointed custodians of land (Mkandawire et al., 1990). Smallholder farmers do not have formal private property rights rather they only have use rights. In practice though, individuals have exclusive rights to the land they cultivate and will pass it on from one generation to the next within the family line. Effectively, smallholder land informally becomes a family property and as such, most families will usually have a private incentive and self interest to sustain productivity of the land for future generations. In this case externalities are assumed internalised.

It is assumed that individuals have strong incentives as private owners to conserve soil quality and that individual optimisation behaviour corresponds to the dynamic social optimisation in the absence of externalities that cause private and social costs to diverge. The present study employs an optimal control framework to maximise the sum of discounted net benefits from use of soil quality (soil nutrients) in the production of agricultural output Q. Accordingly, the dynamic optimisation decision problem of the landowner is specified as:

$$\underset{(Q_t)}{Max}(\Pi_t) = \int_0^\infty e^{-\delta t}(P_t Q_t - C_t(Q_t))dt \qquad (1)$$

where Π_t is profit at time t, Q_t is agricultural output level, P is per unit output price, C_t is the cost of producing output Q at time t. The output and input prices faced by individual decision makers are assumed to be exogenously determined[10]. δ is the social discount rate, which accounts for the central question of relevance of time in dealing with optimal natural resource use.

McConnell (1983) provides an example of the use of dynamic optimisation (maximum principle) to model the problem of land degradation for farmers in Palouse (USA). McConnell (1983) approached this problem by focussing on effects of rooting depth (soil physical structures) on productivity. A key assumption he made was that soil quality (nutrient stock) was constant since farmers applied enough fertiliser to replenish the soil nutrients. While this assumption might be true for most developed countries, most countries in SSA, including Malawi, are faced with serious problems of nutrient depletion. Smallholder farms are continuously cultivated, which when coupled with low application of external inputs leads to depletion of soil nutrients. As such, land quality cannot be constant as assumed by McConnell (1983). Soil mining is actually the most important form of soil degradation in SSA (see Stoorvogel and Smaling, 1990). However, this does not imply that the effects on productivity of soil physical structure destruction are of less importance in Malawi. Rooting depth is crucial in soil productivity because it determines soil reserves of water and nutrients (Aune and Lal, 1995). Accelerated soil erosion reduces rooting depth. However, determination of the effects of rooting depth on productivity is quite complex. There is no direct method for measuring the effects of rooting depth (soil physical structure) on productivity (Aune and Lal, 1995). Most studies that have tried to link land productivity and soil physical structure destruction (rooting depth) have assumed a linear relationship between the two (see Brekke et al, 1999; McConnell, 1983). In other words, reduction in rooting depth lowers soil productivity, which reduces yield.

Considering the severity of nutrient depletion in Malawian smallholder agriculture, the present study mainly focuses on the soil-mining problem due to imbalanced nutrient replenishment through external sources, nutrient extraction by crop harvest and nutrient loss

[10] If one considers a central agency acting on behalf of all individual farmers to find a social optimum, then prices may become endogenous to the decision making problem as the case of monopolistic decision (Dasgupta and Heal, 1979).

due to soil erosion process. Low input application by smallholder farmers in Malawi entails that more soil nutrients are being lost than are replaced through external sources such as organic and inorganic fertilisers. Land productivity in this soil-mining model is assumed to be a function of soil nutrient stock S. In this formulation, it is assumed that the effect of soil erosion on soil physical properties (e.g., rooting depth) represents less of a threat to productivity compared to its effect on reducing nutrient stocks, which is the main constraint on land productivity (Brekke et al, 1999). In other words, the underlying assumption in this formulation is that the linkage between land productivity and soil erosion is not complicated by the negative effect of erosion on soil physical structures.

4.2 Modelling Agricultural Output and Soil Mining

The process of generating agricultural output is modelled in this section based on the production decision environment predominating smallholder semi-subsistence farming characteristics. The basic background of such farming system includes the following circumstances:

1. Labour and soil nutrients are the main inputs in agricultural production with limited capital inputs.
2. Soil fertility is managed mainly through application of commercial fertiliser and limited organic fertilisers are applied to supplement soil nutrients.
3. Labour and limited capital expenditures are used to conserve soil resources.

Based on the above, agricultural output is modelled as follows:

$$Q_t = f(S_t, LQ_t) \qquad (2)$$

In this formulation, agricultural output Q_t depends on the stock of soil nutrients S_t and labour employed in production activities LQ_t. The production process described in equation (2) differs from the way agricultural production technology is typically specified in that the stock of soil nutrients S_t and not the level of fertiliser application influences production. This is based on the fact that actual uptake of nutrients by the growing plant, which depends on available nutrient stock, is the factor determining agricultural production. However, fertiliser application influences output indirectly through its augmenting effect on the stock of soil nutrients as described in the equation of motion given below.

$$\dot{S} = H(Q_t, LS_t, KS_t) - D(Q_t) + G(F_t) \qquad (3)$$

According to equation 3, the stock of soil nutrients is reduced through growth and harvesting of agricultural output according to the depletion (or damage) function $D(Q_t)$. Soil nutrients are replenished by addition of commercial and organic fertilisers F_t, where the function G converts externally applied fertiliser inputs into soil nutrients.[11]

The stock of soil nutrients is also augmented and depleted through a natural regeneration and decay process described by the aggregate function H, which can be thought of as a combination of the following processes:

$$H(Q_t, LS_t, KS_t) = h - M(Q_t, LS_t, KS_t) \qquad (4)$$

where h is a constant measuring the natural inflow of nutrients from external sources (other sites) that is independent of stock levels in the importing plot site but determined by natural factors transporting soil from one site to another, i.e., all erosion forces. All plots also lose soil through the process of erosion, which is modelled as function M (the decay function of H) in equation 4. The decay process depends on the level of output Q (canopy) and conservation efforts through the use of labour LS_t and capital KS_t resources and other management practices. Accordingly, the sign of H could be negative or positive depending

[11] If one assumes that externally applied fertiliser to be a perfect substitute of natural soil nutrient, then the function G maps F into S as a one-to-one relationship, e.g., $G(F_t)$ reduces to only F_t in equation 3.

on the net effect of natural augmentation and decay processes and efforts at any given period t[12].

Farmers also use land to manage fertility and conserve soil resources when land is not limiting. This is the typical situation where farmers practice shifting cultivation or fallow rotations. In the case of smallholder farmers in Malawi however, this is not the case as land is limiting and no such opportunity is available to exploit at the extensive margin as discussed in earlier sections.

The production function $Q_t = f(S_t, LQ_t)$ given in equation 2 is assumed to satisfy all regularity conditions and properties of admissible technology structure (continuous, twice differentiable and strictly concave (Chambers, 1988)). Properties of the other functions H, D and G given in equation 3 will be specified in the empirical sections of the next chapter.

4.3 The Optimal Control of Soil Quality Depletion

From the above it follows that the objective of the decision maker (farmer) is to maximise the discounted sum of the stream of net benefits from the use of soil quality stock to produce agricultural output Q (equation 1). Incorporating the structure of the production technology (equation 2) subject to the equation of motion of the state variable (soil quality stock), specified in equation (3), the optimal control problem over an infinite time horizon can be given by:

$$\underset{(KS_t, LQ_t, LS_t, F_t)}{Max} \Pi_t = \int_0^{\infty} e^{-\delta t}\left[P_t f(S_t, LQ_t) - w_F F_t - w_K KS_t - w_L(LQ_t + LS_t)\right]dt \qquad (4)$$

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[12] Note that while LS and KS reduce decay $\left(\frac{\partial M}{\partial LS} \& \frac{\partial M}{\partial KS} \leq 0\right)$ higher stock levels may contribute to increased decay or erosion implying $\left(\frac{\partial M}{\partial S} \geq 0\right)$ and hence $\left(\frac{\partial H}{\partial S} \leq 0\right)$, if one wishes to model M as a function of stock S, an effect this study did not consider. On the other hand, more dense canopy (Q) reduces decay (less erosion), i.e. $\frac{\partial M}{\partial Q} \leq 0$ and hence $\frac{\partial H}{\partial Q} \geq 0$

Subject to:

$$\dot{S}_t = H(Q_t, LS_t, KS_t) - D(Q_t) + G(F_t)$$

S_0 is given

$$\frac{\partial f}{\partial S} \& \frac{\partial f}{\partial LQ} \geq 0,\ \frac{\partial H}{\partial LS} \& \frac{\partial H}{\partial KS} \geq 0;\ \frac{\partial D}{\partial Q} \geq 0;\ \frac{\partial G}{\partial F} \geq 0$$

Where Π_t is discounted stream of net benefits over time, which in general is considered to be the correct measure of value of the land in production. P, w_F, w_K, and w_L are output, fertiliser, capital, and labour input prices, respectively[13], and δ is the social discount rate.

The Hamiltonian function N associated with the above dynamic choice problem can be formulated as:

$$N(F, LQ, LS, KS, \lambda) = e^{-\delta t}\left[Pf(S_t, LQ_t) - w_F F_t - w_K KS_t - w_L(LQ_t + LS_t)\right] + \lambda_t\left[H(Q_t, LS_t, KS_t) - D(Q) + G(F_t)\right] \qquad (5)$$

The first order conditions for optimal control (FOC)

$$\frac{\partial N}{\partial F_t} = 0 \Rightarrow e^{-\delta t} w_F = \lambda_t G_{F_t} \qquad G_{F_t} = \frac{\partial G}{\partial F_t} \qquad (6)$$

$$\frac{\partial N}{\partial LS_t} = 0 \Rightarrow e^{-\delta t} w_L = \lambda_t H_{LS_t} \qquad H_{LS_t} = \frac{\partial H}{\partial LS_t} \qquad (7)$$

$$\frac{\partial N}{\partial KS_t} = 0 \Rightarrow e^{-\delta t} w_K = \lambda_t H_{KS_t}; \qquad H_{KS_t} = \frac{\partial H}{\partial KS_t} \qquad (8)$$

$$\frac{\partial N}{\partial LQ_t} = 0 \Rightarrow e^{-\delta t}\left(Pf_{LQ_t} - w_L\right) = \lambda_t\left(D_{LQ_t} - H_{LQ_t}\right); D_{LQ_t} = \frac{\partial D}{\partial LQ_t}; H_{LQ_t} = \frac{\partial H}{\partial LQ_t};$$

$$f_{LQ_t} = \frac{\partial f}{\partial LQ_t} \qquad (9)$$

[13] Note that the time subscript t has been dropped from input prices for simplicity of presentation.

$$\dot{\lambda} = -\frac{\partial N}{\partial S_t} = -\left(e^{-\delta t} P f_{S_t}\right) + \lambda_t \left[D_{S_t} - H_{S_t}\right]; \qquad D_{S_t} = \frac{\partial D}{\partial S_t}; H_{S_t} = \frac{\partial H}{\partial S_t};\ f_{S_t} = \frac{\partial f}{\partial S_t} \quad (10)$$

The system of equations consisting of equations 6-9 (and their differential with *t*) plus 10 are then solved for optimal levels of KS^*, LS^*, LQ^* S^*, λ^*.

4.4 Interpreting FOCs

The above system of five equations (6-10) defines the optimality conditions for use of soil nutrients over time as discussed below.

Equation 6 requires that commercial fertiliser is used up to the point where the unit cost of acquisition (discounted price of fertiliser $e^{-\delta t} w_F$) is equated to the dynamic (long-term) marginal benefit from adding one more unit of fertiliser input $\lambda_t G_{F_t}$. The dynamic marginal benefit of fertiliser use is the product of the dynamic price (scarcity value or opportunity cost) of a unit of soil nutrient stock λ_t and the marginal contribution of an extra unit of fertiliser to the stock G_{F_t}. Note that if one considers F_t to be a perfect substitute for natural stock of soil nutrients, G will be linear and then $G_F = 1$, i.e., one unit of F adds one unit of S. This will then reduce the optimality condition of fertiliser use (equation 6) to the equity between present unit cost of buying F ($e^{-\delta t} w_F$) to the unit benefit from conserving a unit of soil nutrient stock for future use (user cost, or dynamic price λ_t).

Equations 7 and 8 determine the optimality conditions for using labour and capital inputs to conserve soil quality stock, respectively. Similar to commercial fertiliser, the use of labour and capital for soil conservation is optimised at the point where the discounted unit cost of the two inputs ($e^{-\delta t} w_L$ & $e^{-\delta t} w_K$) is equated to the marginal benefits of their contribution to maintaining the stock of soil nutrients. However, the use of labour and capital resources for soil conservation contributes through slowing the stock decay process as governed by function H. Labour is also used in the production of agricultural output Q.

Equation 9 indicates that at any point along the optimal path, present net marginal returns to labour use $e^{-\delta t}\left(Pf_{LQ_t} - w_L\right)$ should be equated to the net social (dynamic) cost $\lambda(D_{LQ} - H_{LQ})$ of using an extra unit of labour to produce Q. The net social cost of using an extra unit of labour comprises D_{LQ}, the marginal reduction of soil nutrients stock due to use of extra unit of labour to produce Q which removes nutrient stock through damage function D, and hence the dynamic costs of lower nutrient stock in the future. While H_{LQ} is the marginal contribution to the soil nutrient stock through the use of an extra unit of labour to produce higher Q, which slows down the decay process (reduces erosion) and therefore conserves soil nutrients through H (dynamic benefit in future).

Equation 10 states that the dynamic price (scarcity value) of soil nutrients stock (soil quality) appreciates over time in proportion to the difference between the benefits from using that unit for current production and the opportunity cost to future generations of one less unit of stock $\left(\lambda_t D_{S_t}\right)$[14] due to nutrient extraction by Q. Social benefits from production of Q consist of two components:

a. value of Q produced from an extra unit of soil nutrient stock used, Pf_{S_t}

b. dynamic benefits from more dense canopy (Q) $\lambda_t H_{S_t}$ [15]which in turn contributes to lower soil decay (erosion) through M and hence conserve soil nutrients.

The above system of five equations (6-10) can be solved to determine optimal levels of the five choice (unknown) variables LQ^*, F^*, KS^*, LS^* & λ^*.

[14] Note that $\lambda D_S = \lambda \frac{\partial D}{\partial Q}\frac{\partial Q}{\partial S} \leq 0$

[15] Note that $\lambda H_S = \lambda \frac{\partial H}{\partial Q}\frac{\partial Q}{\partial S} \geq 0$

4.5 Input Substitution

In the above formulation, the farmer decision problem is to choose the optimal mix of labour, capital and fertiliser and soil nutrients to achieve dynamic optimality. This involves a number of decisions determined by the structure of production technology and soil dynamics. For instance, the farmer needs to allocate his labour resources between production activities (increasing Q through LQ) and soil conservation (LS). Taking the ratio of equations 7&9 the following rule for labour allocation between production activities and conservation is defined:

$$\frac{Pf_{LQ} - w_L}{w_L} = \frac{D_{LQ} - H_{LQ}}{H_{LS}} \qquad (11)$$

Equation (11) defines the rule for optimally allocating labour resources between production of Q and soil conservation, which equates the ratio of net benefits from using labour in production of Q relative to cost of labour w_L (LHS) with ratio of its dynamic benefits and costs in production of Q relative to the benefit of using labour in soil conservation H_{LS} (RHS).

Similarly, the farmer combines fertiliser application and soil conservation labour as governed by the ratio of equations 6&7, which gives the following rule:

$$\frac{w_F}{w_L} = \frac{G_F}{H_{LS}} \qquad (12)$$

Equation 12 indicates that farmers optimally allocate fertiliser for production and labour for soil conservation by equating the ratio of prices of fertiliser and labour to the ratio of the marginal contributions to soil quality (soil nutrients) of fertiliser through G and labour through H (soil conservation). Similar results are also derived from equations (6&8) to define optimality rule for combining fertiliser for production activities and capital for soil conservation and also equations (7&8) for combining labour and capital for soil conservation.

$$\frac{w_F}{w_K} = \frac{G_F}{H_{KS}} \tag{13}$$

$$\frac{w_L}{w_K} = \frac{H_{LS}}{H_{KS}} \tag{14}$$

Equation 13 indicates that farmers optimally allocate fertiliser for production and capital for soil conservation at the point where the ratio of prices of fertiliser and capital are equal to the ratio of the marginal contributions to soil quality (soil nutrients) of fertiliser through G and capital through H (soil conservation). Similarly, equation 14 establishes a rule for optimal allocation of labour and capital for soil conservation by equating prices of labour and capital (wage-capital ratio) to the ratio of their marginal contribution to soil quality (soil nutrients) i.e., ratio of the marginal contribution of extra unit of labour and capital to maintaining the stock of soil nutrients through soil conservation.

Finally, ratios of equations 8&9 define an optimality rule for allocating labour for production activities and capital for soil conservation as below:

$$\frac{NP_{LQ}}{w_K} = \frac{D_{LQ} - H_{LQ}}{H_{KS}} \; ; \qquad NP_{LQ} = Pf_{LQ} - w_L \tag{15}$$

According to equation 15, labour for production of output Q and capital for soil conservation should be combined by equating the ratio of net benefits from using labour in production Q relative to price of capital w_L (LHS) with ratio of its dynamic benefits and costs in production of Q (Q conserves soils through canopy cover but also reduces soil quality i.e., extracts nutrient stock) relative to the benefits of using capital in soil conservation H_{KS} (RHS).

4.6 Socially Optimal Use of Soil Nutrient Stock

A socially optimal program for management of soil nutrient stock can be obtained from a desirable steady state (SS) solution of the above model (optimal control model). The SS solution maintains soil nutrient stock at a fixed optimum level indefinitely with a well-implemented policy of a constant but positive royalty (implicit price) on soil nutrient extraction. To derive the SS solution for the above optimal control model, the change in both S and λ is set equal to zero (constant soil nutrient stock and shadow price over time). Using the Current Value Hamiltonian formulation a SS solution is derived in Appendix 1, which requires the satisfaction of following fundamental equations of renewable resource (SS) optimality condition:

$$\frac{Pf_S G_F}{w_F} = \delta + (D_S - H_S) \tag{16}$$

$$\frac{Pf_S H_{LS}}{w_L} = \delta + (D_S - H_S) \tag{17}$$

$$\frac{Pf_S H_{KS}}{w_K} = \delta + (D_S - H_S) \tag{18}$$

$$\frac{Pf_S (D_{LQ} - H_{LQ})}{NP_{LQ}} = \delta + (D_S - H_S) \tag{19}$$

SS optimality conditions provided in equations 16-19 have interesting economic interpretations. The terms on *LHS* of the system 16-19 measure the ratio of the marginal benefits (value of marginal product of inputs) and costs (w_i) of using fertiliser, labour and capital in production of Q and soil conservation $(H_{KS} \;\&\; H_{LS})$. Value of marginal product of inputs is the product of the value of marginal product of soil nutrient stock Pf_S and the marginal contribution of inputs to soil quality $(G_F \;\&\; H_i)$. Use of an extra unit of fertiliser contributes to soil quality via the soil nutrient augmenting function G. While use of extra unit of capital and labour contributes to soil quality through gains from soil conservation efforts that slow down the decay process (H_i). The first term on RHS is the social discount rate. The second term on RHS is the net marginal growth rate of soil nutrient stock S (stock externality effects) and comprises marginal rate of natural stock regeneration H_S and soil nutrient stock degradation through the damage function D_S. The optimality conditions presented in equations 16-18 indicate that the value of the marginal products of inputs (marginal benefits from using one unit of input i) relative to their respective prices must equal the rate of social discount plus the net marginal growth rate of the soil nutrient stock (stock externality effects).

However, the value of marginal product (LHS) in equations 19 is slightly different. It comprises the marginal value product of soil nutrient stock Pf_S and the marginal dynamic cost and benefit of using an extra unit of labour in the production of Q. As mentioned earlier, use of extra unit of labour in production of Q has future costs since higher Q extracts and reduces soil nutrients through damage function D. At the same time higher Q slows down the decay process (erosion) through H and therefore leads to social benefit. The term on LHS is therefore, a ratio of the value of net marginal contribution of production labour LQ to soil quality through Q relative to the marginal returns to labour. Thus, the optimality condition in equation 19 equates the value of marginal product of labour in production of Q to the rate of social discount plus the net marginal growth rate of soil nutrient stock (stock externality effects).

Note that in the absence of soil stock externalities $(H_S = D_S = 0)$ or if the marginal rate of natural soil nutrient regeneration is equal to marginal rate of soil nutrient degradation $(H_S = D_S)$, then the ratio of marginal benefits and costs of using labour, fertiliser and capital in production of Q and soil conservation on LHS will be equated to the social discount rate on RHS at the SS (equations 16-19).

4.7 Comparing Dynamic with Static Optimisation Solutions of Farmers

Since production costs $C(Q)$ included in the $\prod$ function 4 are entirely private, farmers are likely to fully consider these costs in their production decision. On the other hand, unless they are forced by regulation or taxation, farmers will not take into account the full extent of dynamic costs (externality effects) of degrading their soils $\lambda(\cdot)$. In this case the decision problem reduces to a static optimisation problem. This can be seen from setting $\lambda = 0$ in objective function N (equation 5) and the FOC equations will reduce to the static optimisation solutions of the $Pf_i - w_i = 0$ or $Pf_i = VMP_i = w_i$. Thus marginal value product (private benefits) is simply equated to the market price of inputs. Comparison of the current practice to the static and dynamic optimisation will help evaluate whether or not smallholder farmers take into account the dynamic costs in their production practices and also, help to evaluate by how much the current soil management or practices deviate from the social optimum.

CHAPTER V

SPECIFICATION OF THE OPTIMAL CONTROL MODEL, EMPIRICAL RESULTS, DISCUSSION AND CONCLUSION

This chapter applies the dynamic optimisation framework described in chapter IV to the soil-mining problem in Malawi. The specified model is used to solve the soil-mining problem among smallholder maize farmers in Malawi. Empirical estimation of the specified model parameters was then performed. Data sources and econometric procedures used for estimation of model parameters are discussed in section 5.3.

5.1 Specification of the Empirical Soil Mining Model for Malawi

The analytical optimal control model developed in the previous chapter is empirically specified and solved in this chapter. The key components of the analytical model that need to be empirically specified are the production function in equation 2, the aggregate function H that describes the natural regeneration and decay process in equation 4, the depletion (or damage) function $D(Q)$ in equation 3 and lastly, the function $G(F)$ externally supplying nitrogen that augments soil nitrogen in equation 3.

A. In order to determine the smallholder production technology that links soil degradation (soil-mining) to maize productivity, a Cobb Douglas (CD) form was specified for the agricultural production function in equation 2. As the CD is easily linearised in logarithms, coefficients of this log-linear model estimate elasticities (Green, 2000).[16] The CD production function is empirically specified as below:

$$Q = A * LQ^{\alpha_L} S^{\alpha_S} \tag{20}$$

In this formulation, agricultural output Q is a function of production labour LQ and soil nutrient stock S.

[16] The performance of alternative functional forms will be tested later in the parameter estimation sections.

B. The aggregate function H in equation 4 has two main components and these are the natural regeneration h and the decay process $M(Q, LS, KS)$. The natural regeneration h measures the natural inflow of nutrients from external sources (other sites) and is empirically specified as a constant in this study. However, the decay function $M(Q, LS, KS)$ is a function of agricultural output Q (canopy) and farmers' soil management efforts in soil conservation practices through use of labour LS and capital KS. Q and soil conservation efforts reduce the rate of the decay process (erosion) and therefore increase H.

Following Brekke et al. (1999), rate of soil erosion and Q are linked through the following equation:

$$E_t = \phi e^{-bQ} \tag{21}$$

According to this formulation the rate of soil erosion can be manipulated by choosing levels of Q, where higher Q means more dense canopy and hence reduced soil erosion rate. As E_t measures tonnage of soil lost through erosion, one needs a conversion factor β to convert soil loss into equivalent soil nitrogen lost. Hence soil nitrogen lost through soil erosion is measured as $\beta E(Q) = \beta\phi e^{-bQ}$. β is a constant measuring soil nitrogen in kilograms per unit soil depth (cm).

C. Decay process M is also slowed down by contribution of soil conservation efforts through the use of labour (LS) and capital (KS). Contribution of soil conservation to the decay process is specified in this study as CD function below:

$$c = LS^{\beta_1} KS^{\beta_2} \tag{22}$$

Accordingly, the decay function M is specified as an additive function below:

$$M = \left(\beta\phi e^{-bQ} - LS^{\beta_1} KS^{\beta_2}\right) = \left(\beta E(Q) - C\right) \tag{23}$$

Note that use of labour and capital for soil conservation reduce decay and hence the negative sign on the additive term. The aggregate natural regeneration and decay process function H is therefore empirically specified as below:

$$H = h - M = h - \left(\beta\phi e^{-bQ} - LS^{\beta_1} KS^{\beta_2}\right) \tag{24}$$

D. The depletion (or damage) function $D(Q)$ in equation 3 measures nitrogen extraction as a result of harvesting agricultural output Q. Following Brekke et al (1999), the depletion function is empirically specified as a linear function of Q:

$$D(Q) = nQ \tag{25}$$

Note that n is a constant measuring the amount of soil nitrogen removed per ton of output harvested.

E It has been assumed in this study that fertiliser only influences output Q indirectly by augmenting soil nutrient stock via $G(F)$ in the equation of motion (equation 3). The nitrogen augmenting function $G(F)$ is specified as a linear function of fertiliser F as below:

$$G(F) = gF \tag{26}$$

g is a conversion factor, which can take the value of one implying that one unit of fertiliser add one unit of nutrient stock S (i.e., F is a perfect substitute of S).

5.2 Solutions of the Optimal Soil Mining Model

After incorporating the various functional forms specified above (equations 20-26) in the objective function 5 (Hamiltonian) the FOC of the optimisation problem will be as follows (see detailed derivation in Appendix 2):

$$\frac{\partial N}{\partial F} = e^{-\delta t}\left(w_F\right) = \lambda g \quad (27)$$

$$\frac{\partial N}{\partial LQ} = e^{-\delta t}\left(\alpha_L P * A * LQ^{\alpha_{L-1}} S^{\alpha_S} - w_L\right) = \lambda\left[\alpha_L A * LQ^{\alpha_{L-1}} S^{\alpha_S}(n + \beta\zeta)\right] \quad (28)$$

$$\frac{\partial N}{\partial LS} = e^{-\delta t} w_L = \lambda \beta_1 LS^{\beta_1 - 1} KS^{\beta_2} \quad (29)$$

$$\frac{\partial N}{\partial KS} = e^{-\delta t} w_F = \lambda \beta_2 LS^{\beta_1} KS^{\beta_2 - 1} \quad (30)$$

$$\dot{\lambda} = -\frac{\partial N}{\partial S} = -\left(e^{-\delta t} P \alpha_S A * LQ^{\alpha_L} S^{\alpha_S - 1}\right) + \lambda\left[\alpha_S A * LQ^{\alpha_L} S^{\alpha_S - 1}(n + \beta\zeta)\right] \quad (31)$$

$$\dot{S} = h - \left(\beta\phi e^{-bQ} - LS^{\beta_1} KS^{\beta_2}\right) - nQ + gF \quad (32)$$

The above system of six equations can be solved for optimal levels of the six unknowns LQ, LS, KS, F, λ and S using the optimal control approach.

5.2.1 Steady State (SS) Solutions

SS solutions for optimal levels of the listed unknown variables can be obtained by solving the system of SS equations 16-19 in Chapter IV (specified in Appendix 2) plus equation 32. The reduced form solutions for the SS levels of the choice variables are given below and detailed derivations are found in appendix 2.

$$LQ^* = A^{\frac{1}{\gamma}}\left(\frac{w_L}{\alpha_L}\right)^{\frac{1-\alpha_S-\alpha_L+\alpha_S\alpha_L}{\gamma(\alpha_L-1)}}\left(\frac{\delta w_F}{\alpha_S}\right)^{\frac{-\alpha_S}{\gamma}}\left[Pg - w_F(n+\beta\zeta)\right]^{\frac{1}{\gamma}} \quad (33)^{17}$$

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[17] Where $\gamma = 1 - \alpha_1 - \alpha_2$ and $\varphi = 1 - \beta_1 - \beta_2$

$$S^{*} = A^{\frac{1}{\gamma}}\left(\frac{\alpha_L}{w_L}\right)^{\frac{\alpha_L}{\gamma}}\left[\frac{w_F\delta}{\alpha_S}\right]^{\frac{\alpha_L-1}{\gamma}}\left[Pg - w_F\left(n+\beta\zeta\right)\right]^{\frac{1}{\gamma}} \tag{34}$$

$$LS^{*} = \left(\frac{\beta_1}{w_L}\right)^{\frac{1-\beta_1}{\varphi}}\left(\frac{\beta_2}{w_K}\right)^{\frac{\beta_1}{\varphi}}\left(\frac{w_F}{g}\right)^{\frac{1}{\varphi}} \tag{35}$$

$$KS^{*} = \left(\frac{\beta_1}{w_L}\right)^{\frac{\beta_1}{\varphi}}\left(\frac{\beta_2}{w_K}\right)^{\frac{1-\beta_1}{\varphi}}\left(\frac{w_F}{g}\right)^{\frac{1}{\varphi}} \tag{36}$$

Equations 33 & 34 give the reduced form equations for computing the SS optimal level of labour and soil nitrogen stock S for production of Q. Similarly, equations 35 & 36 give the reduced form equations for calculating the SS optimal levels of labour and capital, respectively, for soil conservation.

However, SS optimal level of fertilizer F can be calculated from equation 32 $\left(\dot{S} = H - D + G\right)$. At steady state (SS), $\dot{S} = 0$, therefore $G = D - H$ (Appendix 2):

$$F = \left(\begin{array}{l} nA^{\frac{1}{\gamma}}\left(\frac{w_F\delta}{\alpha_S}\right)^{\frac{-\alpha_S}{\gamma}}\left(\frac{\alpha_S}{w_L}\right)^{\frac{\alpha_S\alpha_L{}^2+\alpha_L-\alpha_L{}^2}{\gamma}}\left[Pg - w_F\left(n+\beta\zeta\right)\right]^{\frac{\alpha_S+\alpha_L}{\gamma}} + \beta e^{-bQ} + \\ \left[\left(\frac{\beta_1}{w_L}\right)^{\frac{\beta_1}{\phi}}\left(\frac{w_K}{\beta_2}\right)^{\frac{-\beta_2}{\phi}}\left(\frac{w_F}{g}\right)^{\frac{\beta_2+\beta_1}{\phi}}\right] - h \end{array}\right) / g \tag{37}$$

5.3 Estimation of the Specified Model Parameters

The dynamic optimisation framework described in Chapter IV was applied to the soil-mining problem among smallholder maize farmers in Malawi. This section describes the sources and methods of data collection and the empirical estimation of the model parameters in specified sections.

5.3.1 Sources and methods of data collection

The alarming levels of land degradation through soil erosion in Malawi has in recent years forced the government to take some counteracting measures to curb or limit this problem. In such vein, the government of Malawi with support from USAID, embarked on a project in the mid 1990s to monitor soil erosion in some identified districts and also, introduced some small-scale soil conservation technologies to smallholder farmers in the study areas. The project was unsuccessful in most of the districts it was introduced. However, Mangochi district in the Southern Region and Nkhata-Bay district in the Northern Region of Malawi were the only districts with reliable erosion data collected under this government supported soil conservation project. The marker ridge was one of the main soil conservation technologies that were introduced and experimented by smallholder farmers in these districts. Data for the current study were collected from these areas after at least two years had elapsed since the trial phase of this said government project was concluded.

Some 2150 households were introduced to soil conservation technology (marker ridge) in Mangochi and Nkhatabay districts. Mangochi contributed about 55 per cent while Nkhatabay contributed 44 per cent of the population. A total sample size of 263 farm households was randomly drawn while maintaining the above representation of the district contributions to the population. Thus, Mangochi contributed 143 and Nkhata-Bay district contributed 120 farm households. The sampled households were stratified into those who continued with the technology (adopters) and those that dropped out after the project phase (non-adopters). A structured questionnaire was administered to the household heads. However, due to the problem of incomplete data for some questionnaires, only 260 households were used in the analysis. Data for the smallholder maize production and soil conservation practices were collected and included *inter alia*; yield levels, total land size, fertiliser use, labour-hours for production and soil conservation, and capital use for soil conservation (see appendix 3).

Maize is grown in all the regions of the country. However, the choice of these two regions was mainly influenced by availability of better soil erosion data. Since only minimal differences exist among smallholder farmers in Malawi in terms of input use and maize yield levels, these data can be considered representative of smallholder farmers in the country. A soil survey to establish the characteristics of the major soils was also carried out in the selected regions. Secondary data were also used for the empirical specification of various parameters. Secondary data were obtained from the Ministry of Agriculture and Irrigation (MoAI), the Farming Early Warning System (FEWS), the National Economic Council (NEC), the National Statistic Office (NSO) and the International Fertiliser Development Centre (IFDC) reports, *inter alia.*

5.3.2 Estimation of Cobb Douglas (CD) production function

As indicated in the above section, smallholder maize production survey data for 2001 agricultural season were used to estimate a CD production function (equation 20). When working with survey data observed input and output levels may be jointly determined (Hallam et al, 1989). This implies heteroscedasticity rendering ordinary least squares estimators (OLSE) inconsistent. Accordingly, the White's estimator (Green, 1997) was used to correct for possible heteroscedasticity in estimation of the CD production function parameters. As such, least squares procedure may lead to bias and inconsistence in parameters.

$$\ln Q = \alpha_0 + \alpha_L \ln L + \alpha_S \ln S + \varepsilon$$

where:

$\ln Q$ = natural logarithm of maize yield (kg/ha)

$\ln L$ = natural logarithm of labour in production of maize (labour-days/ha)

$\ln S$ = natural logarithm of soil nitrogen (kgN/ha)

ε = Error term

Noteworthy, soil nitrogen is a highly labile property and no single soil analysis is adequate to predict its supply to crop over the growing season (Aune and Lal, 1995). As such, although output Q has been formulated in this study to be a function of soil nutrient stock S, the estimated nitrogen coefficient (elasticity) is based on crop response to N- fertiliser application. In a similar approach, Brekke et al. (1999) in measuring soil wealth for Tanzania, adapted nitrogen coefficient $(\alpha_N = 0.3)$ computed by Aune and Lal (1995) based on a 17-year soil experimental data of crop response to N-fertiliser from Kasama in Zambia. The lower fertiliser coefficient for smallholder farmers in Malawi (Table 9), as opposed to that computed by Aune and Lal (1999), could mean that soils in Malawi are more degraded (i.e., below threshold) and therefore obscures true potential gains from the use of fertiliser (see Hardy, 1998). Noteworthy, use of capital for production among smallholder farmers in Malawi is quite insignificant and was therefore not included in the estimation of the production function. Similarly, seed was also not considered since most smallholder farmers were unable to give reliable estimates of the amount they used in production.

Table 9: Parameter estimates of the CD production function for smallholder maize in Malawi (2001)

Variable name	Coefficient values	T-Ratio	P-value
Constant	α_0 1.5 (0.98)	1.5	0.12
$\ln L$	α_L 0.53 (0.16)	3.34***	0.001
$\ln F$	α_F 0.18 (0.07)	2.55**	0.01
Adj R^2	0.19		
F-statistic	2.01		0.08

Figures in parentheses are standard errors; *** Statistically significant at 1% level; ** statistically significant at 5%.

As shown in Table 9, coefficients (elasticities) for labour and fertiliser inputs have the right signs and are both statistically significant at 5%. The low R^2 value of 0.19 is mainly due to the fact that cross sectional data were used for the analysis [Mitchell and Carson, 1993; Pindyck and Rubinfeld, 1998]. The magnitude of labour coefficient implies that it is the most important determinant of smallholder maize yield in Malawi.

5.3.2 Measuring parameters of the soil depletion and regeneration functions

In the model linking erosion and Q (equation 21), parameters ϕ and b depend on the slope and rainfall intensity. Stockings (1986) already specified these parameters for Zimbabwe and they also apply for most countries in Southern Africa including Malawi. Rate of soil erosion was estimated in tons per hectare using the soil loss estimation model for Southern Africa (SLEMSA). A geographic information system (GIS) approach was used to estimate soil erosion rates. A national average erosion rate of 20 tons/ha was estimated under the current production practices in Malawi. Shiferaw and Holden (1999) and Brekke et al. (1999) have indicated that 100 tons of soil loss are equivalent to one centimetre of soil depth lost. Hence 20 tons/ha are equivalent to 0.2 centimetres of soil depth lost.

The level of nitrogen per unit soil depth "β", was estimated through a soil survey carried out as part of the study in Southern and Northern Regions of Malawi in 2001. This study focussed on the effects of nitrogen levels on soil productivity since it is the most important soil element for maize production in Malawi. A chemical soil analysis was conducted at Bunda College of Agriculture to determine levels of some key elements of these soils. The chemical analysis revealed that on average, most soils in Malawi contain nitrogen levels of about 70kg per cm soil[18]. The top 20cm of soil is considered crucial for maize production (Aune and Lal, 1995). Hence, 70kg/cm translates to 1400 kg N (using 20 cm soil depth) as the initial soil nutrient stock (S_0). However, it should be borne in mind that this value is based on the soils that have already been eroded and may underestimate the true level of initial soil nutrient stock.

To calculate total amount of nitrogen lost through soil erosion, the estimate for nitrogen found per unit soil depth β is simply multiplied by the estimated rate of soil erosion taking place i.e., actual soil depth lost through soil erosion associated with level of output Q.

In the damage function nQ (equation 25), parameter 'n' is a constant measuring amount of nitrogen removed through crop harvest in kilograms per ton of maize. The "n" values for Malawi were obtained from the International Fertiliser Development Centre (IFDC, 1999) reports. The nitrogen extraction values were as follows: 16.1kg/ton found in the product and 11.9kg/ton in residues, making a total of 28kg nitrogen extracted per ton of maize harvested. However, in absence of area specific values, these national averages provide a good proxy (IFDC, 1999; Lal and Aune, 1995).

[18] This finding is similar to results found by the Department of Lands Evaluation MoAI, (1991).

Contribution of soil conservation to the decay process has been specified as a Cobb Douglas (CD) function (equation 22). CD function was estimated using ordinary least squares (OLS) based on data collected from farmers' surveys on levels of labour and capital used on farm to conserve soil. Erosion for individual farm plots was estimated using the link between soil erosion and output as formulated in equation 21. Thus, individual farm soil erosion levels were calculated based on individual farm yield levels. The CD model was specifies as below:

$$\ln E_i = \beta_0 + \beta_1 \ln LS_i + \beta_2 \ln KS_i + \varepsilon_i$$

where:

$\ln E_i$ = natural logarithm of soil erosion on farm i

$\ln LS_i$ = natural logarithm of labour for soil conservation on farm i

$\ln KS_i$ = natural logarithm of capital for soil conservation on farm i

ε = Error term

Table 10: Parameter estimates of the CD function of soil conservation

Variable name	Coefficient values	T-Ratio	P-value
$\ln LS$	β_1 -0.17 (0.2)	7.48	0.000***
$\ln KS$	β_2 -0.10 (0.03)	2.49	0.014**
Adj. R^2	0.12		

Figures in parentheses are standard errors; *** Statistically significant at 1% level; ** statistically significant at 5%.

As shown in Table 10, labour and capital input coefficients (elasticities) for soil conservation have the expected signs and are both statistically significant at 5%. The negative sign indicates that soil conservation and soil erosion are negatively related.

The nitrogen augmenting function $G(F)$ (equation 26) was specified as a linear function of fertiliser, $G(F) = gF$. Noteworthy, g is a conversion factor and for lack of better information it is assumed in this study to be one, implying that one unit of fertiliser add one unit of nutrient stock S.

Measuring h in equation 24, is not easy given the limitations of most soil erosion estimation models including SLEMSA[19], which has been used in this study. Instead, and following McConnell (1983), a soil's growth function was introduced and assumed to be constant, θ. McConnell (1983) indicated that rate of natural rebuilding contributes two to five tons of soil per acre per year depending on soil type and weather. On per hectare basis, the natural regeneration θ contributes between 5 to 12.34 tons per hectare per year.

From above, the amount of nitrogen found per unit soil depth β, is estimated to be 70 kg/cm and the natural regeneration process contributes between 5 to 12.34 tons of soil per hectare per year. Following Shiferaw and Holden (1999) and Brekke et al. (1999) conversion rate above, natural regeneration therefore adds between 0.05 and 0.12 cm of soil depth per year. Multiplying the soil depth added per year by the amount of nitrogen found per unit depth of soil, natural regeneration therefore contributes between 3.5 kgN to 8 kgN to the soil nutrient stock per hectare/year. It can be deduced that soil nutrient extraction that exceed 8 kgN/ha is above the threshold i.e., exceeds the maximum rate of soil nutrient natural rebuilding process, and causes a reduction in soil quality in absence of any nutrient supply from external sources to augment the natural regeneration process. Model parameter estimates are also presented in Table 11.

Table 11: Model parameter estimates

Parameter		Estimated value
n (constant for nitrogen extraction through maize harvest)		28 KgN/ton
β (constant for nitrogen level per cm soil depth level)		70kgN/cm soil depth
h (constant for natural regeneration contribution to S stock)		8 kgN/ha
SLEMSA parameters	ϕ	1
	b	-1.204
So (Initial soil nitrogen stock)		1400/ kgN/20cm soil depth

[19] One major limitation of most soil erosion estimation models such as USLE and SLEMSA is their inability to calculate redeposition [Lal, 1990; Morgan, 1988; Foster et al., 1982a; Williams, 1981]

5.4 Using estimated model to determine dynamic optima for soil resources use

The estimated model was used to solve for SS optimal levels of the control variables of the smallholder maize farmer decision problem LQ, F, LS, KS and consequently, the SS optimal stock of soil nutrient S and dynamic price (user cost of soil quality) λ. The model was also used to consider levels of decisions variables under static optimisation formulation e.g., assuming that farmers do not consider the dynamic costs of soil degradation. Dynamic optima at SS were then compared to the static solutions and actual farmers' practices to evaluate the optimality of farmers' decisions with respect to sustainable use of their soil resources. This allows determination of how far current farmers' choices deviate from dynamic optimality.

5.5 Empirical Results of the Optimal Control Model, Discussion and Conclusion

This section summarises and compares results of the SS solutions of the optimal control model, the static optimisation solutions and (SS) and current smallholder production practices. Sensitivity analyses on effects of fertiliser prices, production function coefficients (elasticities) and discount rate on SS input and output levels.

Comparing current smallholder maize output and input use for both production and soil conservation with those of SS, it can be said that current smallholder production is sub-optimal. Of importance to note are the extremely low levels of fertiliser application and capital use for soil conservation under current smallholder farming practices as opposed to the required levels at SS. Current smallholder fertiliser application is one-third of the required amount at SS, while current capital use is about one-quarter of the requirement at SS. Using nitrogen extraction rate of 28kg/ton of maize harvested (IFDC, 1999) nitrogen lost through crop harvest alone under current smallholder practices is estimated at 21kg/ha (nQ). The current smallholder fertiliser application rate of 15kg/ha is below the minimum requirement to offset nitrogen loss through crop harvest alone.

Increasing current output level for smallholder maize farmers (0.75ton/ha) to the SS level of 1.4ton/ha reduces rate of soil erosion from 0.2cm to 0.15cm soil depth. Higher yield results in gains to the soil nutrient stock through reduced soil erosion hence reduced nutrient stock loss. However, increased yield also increases nutrient extraction through crop harvest.

Table 12: Comparative analyses results

Variable	Steady State (SS)	Current Practice	Static Optimisation
Production labour (LQ) (labour-day/ha)	128	90	71
Nitrogen stock (S) ton/ha	1.6	1.4	
Fertiliser (F) kg/ha	49	15	14
Output level (Q) ton/ha	1.5	0.75	0.5
Change in Soil stock (S)	0	-20	
Conservation labour (LS) labour-day/ha	33	27	
Conservation capital (KS) US$/ha	18	4	
Erosion level cm-soil depth/ha	0.15	0.2	0.2
Total user cost of soil quality US$/ha		21	0

However, comparison of the current practice and static optimisation solutions present some interesting results. Static solutions for control variables, output and labour are below those for current smallholder practice. Nitrogen stock under static optimisation is below the current state of 1.4ton/ha. It can be concluded from this analysis that current smallholder practices do not exactly resemble static optimisation solutions. This suggests that smallholder farmers though producing at sub-optimal levels in terms of output and resource use (when compared with SS solutions), somehow have private incentives to conserve the soil (i.e., internalise some of the potential externalities). The study computed a shadow price for soil quality of US$21/ha for the current smallholder practices. Thus, smallholder maize farmers in Malawi somehow internalise some externalities i.e., consider the dynamic costs of soil degradation in their current soil management decisions. Estimated current (initial) level of soil nitrogen stock of 1.4ton/ha was slightly below that of the SS, 1.6ton/ha. The substantially low fertiliser application rate and capital use for soil conservation by smallholders farmers under current practices, was far short from SS requirements. Although smallholder farmers seem to consider dynamic costs of soil degradation to certain extent, they still deviate from the SS optimal path of soil nitrogen resource use. Under current smallholder practice, soil nitrogen stock (S) is declining by 20kgN/ha/year and therefore drifting further away from the SS optimum (Table 12)

5.6 Sensitivity Analysis

Sensitivity of the above model solutions and simulation analysis to variations in some critical values were examined. The values of fertiliser prices and production function coefficients (elasticities) were varied to perform the sensitivity analyses. The model was quite sensitive to the levels of fertiliser prices and production coefficients (elasticities) used. For example, reduction in fertilizer price (from 0.6 to 0.5 US cents, 16.6%) lead to higher levels of external fertiliser application (57kg/ha) to maintain a SS level of soil nitrogen stock of 2.6 tons/ha, indefinitely. However, higher fertiliser and soil nutrient stock at SS due to the fertiliser price reduction induced a higher output at SS (2 ton/ha) than baseline 1.5ton/ha level (Table 13 and 12). Fertiliser price reduction is synonymous to input subsidy or improvement in the input market that leads to competitive fertiliser prices. Considering the usually over stretched budgets and meagre sources of income for most developing countries such as Malawi, improvement in the input market i.e., policies that encourage competition and provision of the necessary market and road infrastructure seem to be a viable option for reducing input prices. Improvement in output prices would have comparable effect as input price reduction.

Coefficient for fertiliser was increased by 0.13 to 0.3 (from 0.17), to match the one used by Brekke et al. (1999). However meaningful results could only be achieved when labour coefficient was reduced to 0.4 (decrease by 0.16). This shift represents a significant maize response to fertiliser use (i.e., increased fertiliser influence in maize production). Sensitivity analysis results indicated an increase in labour use (191 labour-days) and fertilizer amount (88kg/ha) required to maintain a significantly higher level of soil nutrient stock (5.9 ton/ha) at SS indefinitely. Consequently, output increased to 3 ton/ha at SS. From this analysis it is shown that smallholder agricultural productivity would improve if production input mix shifted towards more use of fertilizer or any other alternative that enhances soil fertility.

Thus, fertiliser price reduction and scaling up of fertilizer production coefficient[20] (elasticity) resulted in higher soil nutrient stock and optimal out put at SS. In case of renewable resources like soil, high nutrient stock means high soil quality and therefore increased soils' worth. This may persuade farmers to value soil quality more as the cost of degrading becomes significantly high. This is consistent with McConnell (1983) and Burt (1981) who indicated that a higher marginal user cost of soil usually entails a lower rate of soil degradation (soil erosion) and vice-versa.

Table 13: Sensitivity analyses on some critical values (SS)

Scenario		Steady State (SS)
Fertilizer price reduction (0.6-0.5US cents)		
Labour	(labour-days/ha)	173
Fertiliser	(kg/ha)	57
Maize yield	(ton/ha)	2
Nitrogen stock (S)	(ton/ha)	2.6
Production function coefficients (elasticities)		
Labour elasticity (0.57 to 0.4)		
Fertiliser elasticity (0.17 to 0.3)		
Labour	(labour-days/ha)	191
Fertiliser	(kg/ha)	89
Maize yield	(ton/ha)	3
Nitrogen stock (S)	(ton/ha)	5.9
Discount Rate (Increase from 2-5%)		
Labour	(labour-days/ha)	72
N-Fertiliser	(kg/ha)	29
Maize yield	(ton/ha)	0.8
Nitrogen stock (S)	(ton/ha)	0.4
Increasing soil conservation (US$20 and 40 labour days)		
Labour (labour-days)		178
N-Fertiliser	(kg/ha)	53
Maize yield	(ton/ha)	2
Nitrogen Stock (S)	(ton/ha)	2
Rate of erosion	(cm soil depth/ha)	0.13

SS solutions were highly sensitive to level of discount rate used. For example, slightly increase of discount rate from 2% to 5% lead to sub-optimal levels of both labour and soil nutrient stock SS (Table 13). Optimum output level was close to that currently being produced under current smallholder production. Since current practice solutions for

[20] A proxy to possible technological improvement effect that would increase crop response to fertiliser use.

smallholder farmers resemble closely the SS solutions for higher discount rate (5%), it suggests that smallholder farmers exploit the soil nitrogen resource even though they seem to have private incentive to conserve because they have a high time preference.

Sensitivity analysis on prices of labour and capital for soil conservation showed that reducing these prices induced more use of soil conservation. Increasing capital and labour use for soil conservation influenced a reduction in the rate of soil erosion (Table 13). Optimal output at SS increased to 2ton/ha with some minor upward adjustments in fertiliser use.

CHAPTER VI

FACTORS INFLUENCING INCIDENCE AND EXTENT OF ADOPTION OF SOIL CONSERVATION TECHNOLOGIES AMONG SMALLHOLDER FARMERS IN MALAWI: A Selective Tobit Model Analysis

6.1 Introduction

In the previous chapters, it was established that soil erosion is one of the key factor contributing to soil nutrient depletion among smallholder farmers in Malawi. The curtailment of soil erosion is regarded as crucial in reversing the trend of soil degradation, which is a serious threat to the future productivity of soils. However, low adoption of soil conservation technologies is a major limitation among smallholder farmers in Malawi (Mangisoni, 1999). Nevertheless, understanding the way farmers make their decisions when investing in soil conservation technologies would assist in solving the dilemma on low adoption of soil conservation practices among smallholder farmers, even with clear evidence of profitability of the technologies. In this chapter, factors influencing the incidence and extent of adoption of soil conservation technologies among smallholder farmers in Malawi are investigated. It is envisaged that adoption of soil conserving techniques among the smallholder farmers would only improve if their key problems are known and addressed. This following section will first review briefly some literature on factors that have influenced farmers' decisions to invest in soil conservation.

6.2 Soil Conservation in Malawi

Soil conservation in Malawi has a long history dating back to the colonial period. In the colonial period, before 1964, soil conservation was characterized by coercive methods to force farmers adopt the alien resource conservation technologies which were principally European or British-oriented (Mangisoni, 1999). In the early 1980s, the country witnessed an immergence of biological and small-scale physical conservation techniques that were thought to be better suited for smallholder farmers. In spite of all the efforts to persuade smallholder farmers to conserve their over-cultivated lands, some careless traditional cultivation practices are still being witnessed in many parts of the country (Mangisoni, 1999), with consequences of soil erosion and low productivity of the soils.

Considering the poverty situation in Malawi, small-scale soil conservation techniques are crucial for the curtailment of soil erosion among smallholder farmers. Poverty in Malawi has continued to worsen with more than 70 per cent of farming households classified as poor (FAO, 1998). The growing number of poor households means that fewer and fewer farm families can now afford to purchase the commercial fertilizers. Small-scale soil conservation technologies are vital not only for their effectiveness in reducing soil erosion, but importantly also, for their relative affordability. However, the main limitation for the effective use of soil conservation techniques among smallholder farmers in Malawi has been the low adoption levels (Mangisoni, 1999). It is worthwhile exploring some of the reasons that influence farmers' decisions to invest in soil conservation technologies.

6.3 Investing in Soil Conservation

Dating back to the 1950s, literature on the economics of soil erosion and conservation ascribes a key role to institutional factors, information and attitudes (Ciriacy-Wantrup, 1952). Researchers have emphasised the need to solicit farmers' perception and monitor their decisions (Eaton, 1996). Miranda (1992) emphasised the importance of information and perceptions of the productivity effects of soil erosion. In a study of U.S.A farmers enrolled in a government program, which paid them to remove highly erodible cropland from production, Miranda found that many farmers "did not understand or are failing to act on the on-site productivity effects caused by erosion". Such results underline a crucial information problem facing farmers (Eaton, 1996).

Economic consideration is usually the central issue when farmers decide to invest in any cropping system including soil conservation (Eaton, 1996). Cost-benefit approach of alternative cropping systems has been widely used to assist or guide farmers' investment decision in particular cropping system. It has been argued that marginal productivity of the soil can only be defined with reference to a particular cropping system (Walker, 1982). When faced with a choice to adopt a cropping system, including soil conservation, it is important to calculate the net present value to the farmer of the alternative cropping systems. Thus, one must decide which cropping system to use by calculating future production foregone as a result of choosing some practice today.

Pagiola (1993) conducted a study in the semi-arid region of Kenya focusing on farmers' incentives to conserve. He estimated the damage due to soil degradation and the returns to conservation in Machakos and Kitui districts. The returns to soil conservation were estimated using cost-benefit technique. First, he estimated effects of continued erosion on productivity for a time horizon of interest. Returns were estimated at each specified time. The calculations were repeated under assumption of an investment in conservation measures. The returns to investment were obtained by taking the difference between the streams of discounted costs and benefits in the with-and the-without-conservation cases.

Pagiola (1993) focused on the adoption of terraces. The results of his study indicated that smallholder farmers, *inter alia*, consider profitability of the conservation technologies before fully adopting or investing in them. The study also found that returns from conservation measures were highly sensitive to case-specific characteristics. Under some conditions conservation could not pay for individual farmers. For example, on low slopes, the cost of conservation outweighed the relative small benefits of avoiding low rate of erosion. Pagiola (1993) concluded, therefore, that it would be unrealistic to expect all farmers to adopt the conservation measures.

The difficulty of formally describing farmers' choice of alternative cropping systems prompted other economists, particularly those undertaking empirical work, to adopt a more straightforward cost-benefit approach to analysing soil erosion and conservation decisions (Eaton, 1996). Walkers (1992) developed a damage function model[21]. This essentially calculates the net incremental present value to the farmer of choosing an erosive cultivation practice in the current year as opposed to a more soil conserving practice. An appealing feature of Walker's model is that the decision to adopt or defer soil-conserving practice is taken in each period (Eaton, 1996). Thus if the farmer decides in the current period to continue with an erosive practice, the option is still open to adopt the conservation practice in

[21] The model assumes that farmers are already using erosive practice

the next period. With this assumption, it follows that the marginal user cost of continuing with the erosive practice is the loss in future revenue from delaying by one year the adoption of the conservation practice (Eaton, 1996). This differs from other models (e.g., Ehui et al., 1990) where the loss would be calculated as the difference in future revenue between the erosive and conservation practice, assuming that each is continued throughout the entire planning period (Eaton, 1996). Walker defines the user cost as the amount that is definitely lost due to the current period. This may be thought of as the minimum amount that would be lost by delaying adoption of conservation practice until at least next year (Eaton, 1996). Walker's model was reproduced with some slight modifications and applied in separate studies for Malawi by Eaton (1996) and Mangisoni (1999). Among the important findings from these two studies, it was demonstrated that in the situation of already low yields and low labour productivity in agriculture, soil conserving systems may not be very attractive to the farmer despite significant rate of erosion because the gains from decreasing soil erosion in Malawi do not translate into substantial additional revenue (Eaton, 1996). The simulations also demonstrated that Walker's damage function defines the choice options (farmers' perception of costs and benefits of alternative cropping systems) more accurately than a conventional net present value calculation.

Other studies have considered incentives to invest in soil conservation under uncertainty. Winter-Nelson and Amegbeto (1998) while acknowledging other studies on soil conservation that have included uncertainty [Innes and Ardila,1994; Ardila and Innes, 1993], hinted that most of them have tended to use methods that preclude sunk costs from conservation decisions and usually assume that conservation activities reduce current output. They argued that construction of terraces, for example, have substantial sunk costs and can increase both current and future output. Winter-Nelson and Amegbeto (1998) used an option-pricing model to include output price variability and sunk costs in an analysis of conservation investment under alternative policy regimes in Kenya. This approach was based on their belief that policy reforms to liberalize agricultural markets in developing countries were more likely to influence both the level and variability of prices. Also, that there had been relatively little analysis of the role of price availability in conservation decision.

Winter-Nelson and Amegbeto (1998), indicated that while changes in policy that increase output prices tend to encourage agricultural investment, simultaneous increases in price variability could reduce incentives to invest through a number of channels. First, if individuals are risk averse they might prefer not to adopt a technology exposing them to increased income risk, even if it offers higher average returns (Arrow and Pratt, 1971). Second, if potential investors are credit-constrained due to imperfect capital markets or resource poverty, they may be unable to accumulate funds to make profitable, non-divisible investments, regardless of their risk preference. If such individuals value precautionary savings, they may also avoid committing to projects that cannot be easily liquidated in case of an emergency. Finally, if prices are non-stationary, profit-maximizing investors may value the option to delay an investment and gain more information about future price levels rather than commit to a project (Dixit and Pindyck, 1994). Increased price variability raises the value of the option not to invest immediately and may cause risk-neutral investors with access to finance to postpone investments that appear profitable.

The decision to adopt a conservation technology can be represented as a choice between production with or without a specific conservation output. Under uncertainty, the choice between adopting a new production technology or not can be based on comparison of the incremental investment costs of the new technology and the present value of its incremental net revenue flow (Winter-Nelson and Amegbeto,1998). The results of this study show that indeed increased output price levels tend to improve incentives for agricultural investment, but increased price variability can dampen investment through the effects of risk aversion, credit constraints, or option values. In Kenya, simulations to compare the incentives to invest in conservation under world market prices and lower, more stable administered prices over a period 1964-92 were done. In simulations using world prices rather than administered, the positive effects of higher price levels on incentives to invest is more than off-set by increases in the value of delaying investment due to greater price variability. These results suggest a need to consider the ability of economic institutions to moderate price movements during and after market reforms. If institutions to manage price volatility do not emerge with market deregulation, liberalization could produce undesirable environmental and welfare consequences in the developing world (Winter-Nelson and Amergbeto, 1998).

However, farmers' investment decisions in soil conservation have not always been purely based on profitability and prices. A lot of studies in developing countries have also focused on the socio-economic factors influencing farmers' decision to invest or adopt soil conservation technologies [Feder *et al.*, 1985; Heisey and Mwangi1993; Nkonya et al, 1997; Hassan *et. al.*, 1998; Mangisoni, 1999;]. Most adoption studies are based on censored data, and one of the widely used regressions in these studies is the tobit model. For example, a tobit model with maximum likelihood, was used in Bukina Faso to determine factors that influence farmers' investment in two soil and water conservation techniques (SWC), and these were field bunds and micro-catchments (Kazianga and Masters, 2002). Kazianga and Masters indicated that previous studies of the determinants of SWC had focused on farmers' subjective beliefs and sources of information as well as farmers' material conditions such as farm assets, and factor markets. This particular study aimed to isolate the influence of the relative abundance of land and labour from the property-rights regime that governed cropland (ownership as opposed to user-rights) and grazing (intensive livestock management as opposed to open access grazing). The results suggested that responding to land scarcity with clearer property rights over crop land pasture could help promote investment in soil conservation, and raise the productivity of factors applied to land. Nkonya et al. (1997), using a bootstrapped simultaneous equation tobit model, analysed the adoption of improved maize in Northern Tanzania. The findings of this study were that adoption of improved maize seed was positively related to the nitrogen use per hectare, farm size, farmers' education attainment level, and visits by extension workers. Fertilizer adoption was positively related to the area planted with improved seed. However, larger farms in this area tended to use fertilizer less intensively than smaller farms. The results confirmed the importance of recognizing the heterogeneity of the farming population, not only in terms of differences in the biophysical conditions, but also in the socio-economic, environmental conditions under which they operate (Nkonya et al., 1997).

In many instances, however, factors that influence smallholder investment decisions in soil conservation technologies have been hard to predict at policy level due mainly to methodological limitations. This dilemma has resulted from the fact that the decision making process of smallholder farmers is still not well understood (Goezt, 1992). Failure to understand this process has encouraged prescription of untargeted policy interventions in soil conservation. This study, therefore, aims to contribute towards a better understanding of the sequence of decisions faced by farmers in adopting or investing in soil conservation technologies and the important factors that influence these decisions. Adoption of innovations in general is not a one-time decision as many studies have assumed. Rather, it is a stepwise decision made after weighing carefully opportunity costs at each point [Byerlee and Hesse de Polanco, 1986; Goetz, 1992]. Understandably, farmers always want to avoid unnecessary risks and will, therefore, abandon a technology once their perceived benefits diminish significantly or do not seem to offset costs involved. This may explain why many smallholder farmers abandon a newly introduced technology once it reaches a stage where farmers are supposed to stand alone without any government or donor support (after the project phase). Hence the need to really understand the decision making process of farmers in as afar as adoption of a new technology is concerned.

To simulating the decision making process of smallholder farmers, this study models farmers' adoption decision of soil conservation technologies as a two-step process. The first step is the decision on whether or not to adopt the technology. The second step is to decide how much of the technology to use (extent of adoption or investment). In such an approach, the use of the usual ordinary tobit model has serious limitations since it assumes that the explanatory variables have the same direction of effect on the probability of adoption and on its intensity (Greene, 1997). Kanzianga and Masters (2002) found some evidence that this assumption does not hold using tests developed by Lee and Maddala (1985). Instead a selective tobit model due to its ability to simulate the two-step farmer decision-making process is therefore used. This study considers adoption of marker ridging, a small-scale physical soil conservation technique.

6.4. Approach and methods of the study

As earlier discussed, factors influencing incidence and extent of adoption of soil conservation techniques among smallholder farmers in Malawi were analysed in this study using a selective tobit model. This section discusses the approach and methods, specifies the empirical model, data and data limitations and, household characteristics of the study area.

When data are censored, the distribution that applies to the sample data is a mixture of discrete and continuous distribution (Green, 2000). Adoption studies usually provide such scenario where only part of the population under study participates in a particular technology while others do not. In most cases non-participants face thresholds that can only be surmounted at cost exceeding net benefit realized by participating in the technology (Goezt, 1992). Farmers are usually faced with a two-step decision process. Firstly, farmers decide whether or not to adopt a technology and secondly, decide on their level of involvement or extent of adoption.

The regression model commonly employed in the analyses of adoption decisions is based on a tobit model applied to censored data. Unfortunately, ordinary least squares estimation of the Tobit model yields biased and inconsistent parameter estimates. Heckman (1979) proposed a two-stage estimation process that yields consistent parameter estimates. However, the two-stage estimator involves heteroscedastic errors so that the usual *t* tests are biased. The maximum likelihood estimator is, therefore, found to be the most efficient estimator (Pindyck and Rubinfeld, 1998).

Admittedly, the tobit model is rather restrictive in the sense that a positive (negative) parameter increases (decreases) both the probability of an individual participating in a technology as well as the level of involvement /adoption. As such, the tobit model may not be the most appropriate in cases where farmer's decision to adopt or try a technology is influenced by different set of variables from those that influence the farmer's decision on the level or extent of adoption (Goetz, 1992). A selective tobit model is, therefore, used for the study. This model simulates closely the decision maker's problem. First, whether or not to adopt a technology, and second, if adopted, what level of adoption? In such cases, different policy prescriptions will have to be made depending on whether the government aims to increase the number of farmers participating in soil conservation technologies or persuade those farmers already participating to intensify their involvement. For example, farmers may expand use of technology by allocating more land to soil conservation or increasing labour use.

6.5 Specification of the Empirical Model

This study used selective tobit model employing the maximum likelihood estimation (MLE). Sample selection models (Greene, 1998) share the following structure: A specified model, denoted **A**, apply to the underlying data (equation 6.1). Observed data are, however, not sampled randomly from this population. A related variable Z* is such that an observation is drawn from **A** only when Z* crosses a threshold (i.e., equal to or greater than 1). The general solution to the selectivity problem relies upon an auxiliary model of the process generating Z*. Information about this process is incorporated in the estimation of A.

$$Y = \beta' X + \varepsilon \qquad (6.1)$$

where X is a vector of independent variables and Y is the dependent variable. We assume that the non-random (systematic) process that switches households into soil conservation adoption state, is given by equation 6.2a

$$z_i = \alpha' v + \upsilon_i > 0 \qquad \upsilon_i \sim N(0,\sigma_\upsilon) \qquad (6.2a)$$

$$z_i = 0, otherwise \qquad (6.2b)$$

The sample rule is that z_i and X_i are observed only when Z_i^* is greater than zero and note that y is censored at 0.

The probability that farmer i participates in soil conservation (the response variable Z) depends on a set of explanatory variables X:

$$\Pr ob(z_i = 1) = \Phi(X_i \beta / \sigma) \qquad (6.3)$$

for those with $z_i = X'\beta + \upsilon > 0$ or $z_i > 0 = X'\beta > -\upsilon_i$

$z_i = 0$, otherwise

Here, σ is the standard deviation and $\Phi(.)$ is the standard normal distribution function of the error term υ in equation (6.2a).

The tobit model with sample selection uses the linear prediction of the underlying latent variable

$$E[Y^*|z=1] = \beta'X + \rho\sigma\lambda \qquad (6.4)$$

$$\lambda = \phi(\alpha'Z)/\Phi(\alpha'Z) = \phi/\Phi$$

λ is Mill's ratio or hazard function, displayed and kept for MLE in LIMDEP (Green, 1998).

$\phi = \partial\Phi(X'\beta)/\partial X'\beta$, is the ratio of the marginal to cumulative probability of a household participating in soil conservation. The term λ_i corrects for the bias associated with omitting households not involved in soil conservation when it is included in an OLS regression of non-zero values (regression restricted only to households involved in soil conservation). The predictions are based on linear, single equation specification and they do not exploit the correlation between the primary equation and the selection model. Further manipulation is therefore required.

The tobit model with selection using truncation in a bivariate normal distribution would be as follows:

$$E[y/y>0, z=1] = \beta'x + E[\varepsilon \mid \varepsilon > -\beta \mid x, u > -\alpha'\upsilon] \qquad (6.5)$$

Simplified as:

$$E[\varepsilon \mid \varepsilon > -\beta'x, u > -\alpha'x] = \sigma E[q \mid q > h, u > k],$$

where

$$q = \varepsilon / \sigma,$$
$$h = -\beta' x / \sigma,$$
$$k = -\alpha' z$$

Let $\delta = -1/(1-\rho^2)^{1/2}$

Then, $E[q \mid q > h, u > k] = \{\phi(h)\Phi[\delta(k - \rho h)] + \rho\phi(k)\Phi[\delta(h - \rho k)]\} / \Phi_1$

Thus, $E[y \mid z = 1 = \Phi_1 \beta' x + \sigma\{\phi(h)\Phi[\delta(k - \rho h)] + \rho\phi(k)\Phi[\delta(h - \rho k)]\}$ (6.6)

The probit model precedes the selection tobit model in order to provide starting values for the MLE (Heckman procedure). Noteworthy, results of the probit model (equation 6.3) show which variables determine whether or not a farmer participates in soil conservation. Probit model parameters are used for fitting the sample selection function. However, parameters at this point are still inconsistent since results are obtained by least squares as is the case in any basic tobit model. Parameter estimates are not efficient because the error term is heteroscedastic. Using MLE of the selective tobit model yields consistent and efficient parameters, equation (6.6). This equation computes variables that influence the farmer's decision on the levels of involvement in using the soil conservation technology.

6.6 Choice of Variables

The dependent variable (Y) used for the selective tobit model was the labour required by the household due to its involvement in soil conservation. The study found a close link between labour required by a household due to its involvement in soil conservation activities and the extent of the household's involvement in the technology. It is believed that interesting results could also be achieved if land allocated to soil conservation was used as dependent variable in the selective tobit model. However, most farmers could not precisely indicate the size of land they allocated to soil conservation.

Choice of independent variables in the model was based on a number of factors and assumptions. For example, level of schooling of the head of household is assumed to be key to increasing the level of farmer's understanding and therefore, would positively influence adoption of new technologies (Nkonya et al., 1997). Land ownership can positively or negatively influence adoption depending on who owns the land and who makes farm decisions. Age of household head can be positive or negative depending on position in life cycle. Younger farmers are more likely to be attracted to new technologies and have more need for extra cash (however, limited cash resources may be a constrain), while older farmers may easily be discouraged from adopting new technologies especially if labour demand is so high. Family labour availability may positively influence adoption and extent of adoption as it reduces labour constraint faced by most smallholder farmers.

Increased yield (output levels) is expected to positively affect the extent of technology adoption. Production assets held by the household tend to reflect household's wealth position in most rural households and the more the assets the more likely the household will adopt new technology. Erosion taking place in the field can have positive or negative influence on adoption. Frequently, levels of on-going soil erosion in the field justifies the need for some intervention and, therefore, has a positive influence on adoption of soil conservation technology. However, advanced levels of soil erosion in the field can sometimes force the farmer to abandon the field, especially where land is not scarce. This was experienced in some parts of northern region of Malawi.

6.7 Data and Data Limitations

As described earlier in section 5.3 of chapter 5, the data for this study were collected from farmers' surveys in two districts in the Southern and Northern regions of Malawi during the 2001 agricultural season.

Underreporting of yield data was the most frequently encountered problem, especially in Mangochi district. Apart from the visibly high illiteracy in the district, most respondents also deliberately underreported their yield as they hoped to get some free government handouts of seed and fertilizer, as was the case the previous two years prior to this study. Many farmers, particularly in Mangochi district, could not precisely report land allocated to soil conservation. Some of these problems were spotted during the pre-testing of the questionnaire. Research assistants were taught of the importance of triangulation during interviews as one of the most reliable ways to cross check the information provided by the respondents. The research assistants were also drilled on how to correctly administer the questionnaire in order to minimise enumerator bias.

6.8 Household Characteristics in the Study Areas

The study considered issues such as labour availability, land ownership, type of marriage, education level of household head, age of household head and the period land was under cultivation.

6.8.1 Household type

Among the 260 households considered for the study, male-headed households comprised 74 and 69 per cent of the samples for Nkhata-Bay and Mangochi districts, respectively. Therefore, female-headed households constituted only 26 and 31 per cent of the total households in Nkhata-Bay and Mangochi districts, respectively. While most household heads were monogamists, 65 and 58 percent in Nkhata-Bay and Mangochi districts, respectively, the study found a higher percentage of polygamists in Mangochi district (20%), as opposed to Nkhata-Bay district (5%). Further, 16 per cent of the households in Mangochi district were either divorced or separated as compared to eight per cent in Nkhata-Bay district. Effectively, the number of female-headed households in Mangochi district was about 36 per cent if those under polygamy and the widowed (divorced) were combined. Such a high figure entails some serious labour shortage in critical farming periods for a significant number of farm households in Mangochi district. Most women under polygamy manage farming activities by themselves or sometimes with little help from the husbands.

6.8.2 Literacy level

Another important factor that influences adoption of any new technology among smallholder farmers is literacy level of the household head. The study found that Mangochi has a very high illiteracy level. For example, 51 per cent of the smallholder farmers interviewed in the area had never attended any formal education. Such high illiteracy rate may limit adoption of any new technology. The average age for household heads was 47 and 44 years for Nkhata-

Bay and Mangochi districts, respectively. Therefore, most of the household heads in these districts were economically active.

6.8.3 Land acquisition and land-holding size

Nkhata-Bay and Mangochi districts differ in their marriage systems, patrilineal and matrilineal for the former and the latter respectively. Land ownership in these districts is strongly related to the type of marriage systems being practiced in these areas. For example, 59 per cent of people in Nkhata-Bay indicated that land belongs to the male spouse (husband) and only 24 per cent was under the ownership of the female spouse. However, in Mangochi district land ownership was 38 per cent male and 56 per cent female owned (Table 14). Under customary land, people only have user rights and the chief is the custodian of land. It was not conclusive in this study that land ownership influenced investment decision on the land.

Table 14: Land ownership

Land ownership	District		Total Cases %
	Nkhata Bay %	Mangochi %	
Male spouse	59 (71)	38 (53)	47 (124)
Female spouse	24 (29)	56 (78)	41 (107)
Village headman	5 (6)	3 (4)	4 (10)
Parents	10 (12)	2 (3)	6 (15)
Borrowed	1 (1)	1 (1)	1 (2)
Rent in	1 (1)	1 (1)	1 (2)
Total	100 (120)	100 (140)	100 (260)

Figures in parentheses are number of households

6.8.4 Farming system, soil erosion and soil conservation practices

Maize is the staple food for the majority of Malawians. Maize is usually grown as a monocrop or sometimes intercropped with some legumes such as beans. Even when maize is intercropped with other crops, the main crop is usually maize. This study identified two main smallholder maize technologies and these were local and hybrid maize. Local maize is usually grown without or with minimal amount of commercial fertilizer applied to the crop while hybrid maize needs fertilizer for maximum productivity. However, most smallholder farmers lack capital and cannot easily access credit. Thus most of the farmers only applied limited amount of commercial fertilizers, even to hybrid maize.

Cassava is widely grown in Malawi, including Mangochi district, as a drought resistant crop. However, in Nkhata-Bay district, cassava is the staple food for the majority of the population. Maize is grown in Nkhata-Bay district mostly as a second crop to cassava.

On average land for most smallholder farmers has been cultivated over a long period. For example, more than 47 per cent of the total number of farm households (Mangochi and Nkhata-Bay districts) indicated that they have continuously been cultivating the same piece of land for more than 11 years (Table 15) while 31 per cent of the households had cultivated the same piece of land for more than 20 years. Continuous cultivation of land is an indication of the acute land problem amongst smallholder farmers in Malawi. Coupled with inadequate application of inputs such as commercial fertilizers to replenish soil fertility, soil-mining problem is an obvious predicament among most smallholder farms. Thus soil-mining poses a serious threat to sustainable smallholder agriculture in Malawi. Considering that most smallholder farmers cannot afford commercial fertilizers, soil conservation techniques and use of grain legumes provide viable options for reversing the threat of soil degradation in Malawi.

Table 15: Period land under cultivation

Period (# of years)	District		Total Cases
	Nkhata-Bay %	Mangochi %	%
Less than 5 years	37 (44)	19 (27)	28 (71)
5 to less than 11 years	19 (23)	31 (43)	25 (66)
11 to less than 20 years	14 (17)	18 (25)	16 (42)
More than 20 years	30 (36)	32 (45)	31 (81)
Total number of households	100 (120)	100 (140)	100 (260)

Table 16: Level of soil erosion

Level of soil erosion	District		Total Cases
	Nkhata-Bay %	Mangochi %	%
Mild	40 (48)	20 (28)	29 (76)
Moderate	47 (56)	50 (70)	49 (126)
Severe	13 (16)	30 (42)	22 (58)
Total number of households	100 (120)	100 (140)	100 (260)

Most smallholder farmers in Nkhata-Bay district are experiencing either mild or moderate levels of soil erosion (Table 16). Only 13 per cent of the households in the district indicated that they experienced severe erosion on their fields. Smallholder farmers in Mangochi district experienced mild to the severe type of soil erosion. About 83.1 per cent and 96.5 per cent of smallholder farmers interviewed in Nkhata-Bay and Mangochi districts, respectively, indicated that they had experienced declining yields over the years. Reasons given for the decline were mainly soil erosion, lack of inputs and, erratic and low rainfall (Table 17). Only a small number of households indicated that continuous cultivation of land contributed to the yield decline. This clearly shows lack of proper knowledge by most smallholder farmers on the effects of continuous cultivation on soil fertility.

Table 17: Reasons sighted for yield decline in the area

Reasons for Yield Decline	District		**Total Cases**
	Nkhata-Bay %	Mangochi %	%
Erratic and low rainfall	20	31	26
Lack of inputs	53	71	63
Soil erosion	68	69	68.5
Heavy pest and disease incidences	9	2	5.5
High rainfall	6	31	18
Continuous cultivation of land	5	9	7

6.9 Concluding Summary

Land ownership in Mangochi and Nkhatabay districts is strongly related to the type of marriage systems being practiced in these areas. For example, 59 per cent of people in Nkhata-Bay indicated that land belongs to the male spouse and only 24 per cent was under the ownership of the female spouse. In Mangochi district, land ownership was 38 per cent male and 56 per cent female owned. However, it was not conclusive in this study that land ownership influenced investment decision on the land.

Over 80 per cent of smallholder farmers interviewed in Mangochi and Nkhatabay districts indicated that they had experienced declining yields over the years. More than 47 per cent of the total number of farm households (Mangochi and Nkhata-Bay districts) indicated that they had continuously cultivated the same piece of land for more than 11 years while 31 per cent had cultivated on the same piece of land for more than 20 years. Continuous cultivation of land is an indication of the acute land problem amongst smallholder farmers in Malawi. Coupled with inadequate application of inputs such as commercial fertilizers to replenish soil fertility, soil-mining problem is an obvious predicament among most smallholder farms.

CHAPTER VII

EMPIRICAL RESULTS OF THE SELECTIVE TOBIT ANALYSIS

7.1 Introduction

A selective tobit model was used to analyse factors that influence the incidence and extent of adoption of soil conservation technologies by smallholder farmers in the two districts. The focus of the study was the adoption of the marker ridge by smallholder farmers that were involved in the project. The marker ridge was the most popular small-scale physical soil conservation technology that was introduced to farmers in these study areas.

Separate regression analyses were run for the two districts considering that farmers in these areas were not exposed to the same influences. A district dummy variable was significant indicating that data from the two districts could not be pooled.

Results for the probit and selective tobit models (MLE) are presented in Tables 18 and 19 for Nkhatabay and Mangochi districts, respectively. The probit model analysed variables that are key determinants of whether or not a farmer will choose to participate in soil conservation (adoption of marker ridging). While the selective tobit model results, on the other hand, considered key factors influencing farmers' decision on the extent (level) of adoption, conditional on having adopted the technology.

7.2 Empirical Results and Discussion

Important factors influencing farmers' decision to adopt soil conservation technology (marker ridging) in Nkhatabay district include knowledge of the household head on how soil erosion affects quality of land and productivity, age of household head and land size. All these factors were significant at 10 % level. The signs of the estimated parameters were as expected. Farmers' knowledge about the negative effects of soil erosion on soil quality and productivity and, the importance of soil conservation in combating this problem, was found to have very strong influence on adoption even in areas of high illiteracy levels like

Mangochi district. Although formal education is key to increased farmers' understanding and therefore an important factor influencing adoption of new technologies, imparting the relevant knowledge on the subject matter (e.g., need for soil conservation) to the farmers has far reaching influence especially in rural areas where the majority of farmers have no formal education. The need for extension services cannot, therefore, be questioned in this regard. Age of household head positively influenced adoption, i.e., probability of a household adopting soil conservation techniques increased as age of the household head increased. However, increase in age beyond certain threshold i.e., above economically active category (65 years), affects adoption negatively (Table 18). Marker ridging is labour intensive especially in the first year and could be very taxing for farmers with advanced age in absence of hired labour. Land size is another important variable influencing farmer's decision to adopt soil conservation techniques in Nkhatabay district. Land size has positive influence on adoption of marker ridging techniques i.e., there is a high chance of adoption among farmers owning large pieces of land.

Important factors that influence farmer's decision on the extent of adoption included output level (yield level), labour availability, land size and production assets owned by the household. These were all statistically significant at 10 % level. Although with varying degrees of influence, some factors such as land size were influential at both stages of farmer decision-making i.e., decision to adopt and extent of adoption. When farmers are considering on the extent of adoption, more influential factors are those that affect profitability at farm level e.g., level of output. Increased output can be associated with increased income for the farmers. This result supports the finding by Pagiola (1993), who indicated that smallholder farmers would invest in soil conservation as long as it is profitable.

In Mangochi district, key factors influencing farmers' decision to adopt marker ridging techniques were mainly knowledge of household head, labour availability (number of adults)[22], level of current soil erosion observed in the field and, production assets owned by the household. Knowledge of household head on issues relating to soil erosion and soil conservation technologies relies heavily on extension work in the area. Extension service is vital to improve farmers' understanding of the subject matter, even in areas of high illiteracy

[22] Noteworthy, work study techniques could have provided better estimates for labour

levels. Labour availability was positively related to adoption. Mangochi district had relatively high number of female-headed households (over 30%). As such, labour availability should indeed be one of the most important factors to consider when deciding to adopt any new technology especially when such technology is labour intensive.

Farmer's decision on the extent of adoption was influenced by output level, labour availability, and production assets owned by the household. Knowledge of the household head on the effects of soil erosion on soil quality also influenced the extent of adoption, significance at 10 % level. To a certain extent, results for Mangochi could have been much better if some of the problems experienced during data collection were avoided. However, the results for Mangochi district are still as expected except for the sign in level of erosion variable. Reported pseudo R^2 were 0.30 and 0.35 for Nkhatabay and Mangochi districts, respectively. R-squared for cross-section studies using censored data (binary dependent models) to explain technology adoption usually have a low explanatory power [Goodwin and Schroeder, 1994; Mitchell and Carson, 1993; Pindyck and Rubinfeld, 1998]. An alternative to R^2 is the likelihood ratio index. However, this is usually low as well i.e., not likely to yield close to one for binary dependent model.

Table 18: Factors influencing incidence and extent of adoption in Nkhatabay district

Probit model		
Variables	coefficient	Pvalue
Constant	-4.7375	0.0057*
Land ownership	0.1666	0.9610
Knowledge of hh	1.4695	0.0015*
Number of adult	0.4288	0.7246
Year of schooling	0.7203	0.1528
Age of hh head	0.1648	0.020*
Square age of hh	-0.1926	0.0099*
Land size	0.4408	0.0472*
Yield level	0.6637	0.4746
Level of erosion	0.2179	0.4868
Production assets	0.1267	0.3535
Log likelihood function	-50.36	
R^2	0.30	
Selective Tobit (MLE)		
Constant	-2.5447	0.8163
Land ownership	-	-
Knowledge of hh	8.9712	0.0198*
Number of adult	1.0704	0.1272
Year of schooling	0.2717	0.3454
Age of hh head	-0.1316	0.7894
Square age of hh	0.5627	0.9176
Land size	2.5826	0.0000*
Yield level	0.1941	0.0180*
Level of erosion	-0.3533	0.8948
Production assets	0.3534	0.4549
Log likelihood function	-313.60	

*significant at 10% or lower

Table 19: Factors influencing incidence and extent of adoption in Mangochi district

Probit Equation		
Variable	Coefficients	P value
Const	0.2771	.8092
Land ownership	-0.1391	.6522
Knowledge on erosion	.7429	.0553*
Number of adults (labour)	.1444	.0245*
Age of household head	.2961	.5693
Square age	-0.0013	.8137
Level of erosion	.1074	.0023*
Production assets	.7298	.0215*
Yield level	.2409	.4724
R^2	35	
Log likelihood function	-59.03	
Selective Tobit Equation		
Const	7.8595	.7449
Land ownership	-	-
Knowledge on erosion	2.0059	.0657*
Number of adults	5.0103	.0000*
Age of hh head	1.3493	.1978
Square age	-.9301	.3981
Level of erosion	-.2641	.9633
Production assets	.1054	.0001*
Yield level	.3423	.0000*
Log likelihood function	-646.17	

* significant at 10% or lower

7.3 Concluding Summary

A Selective Tobit Model was used to simulate the two-step decision-making process of farmers with respect to adoption and subsequently, extent of adoption. Results of the empirical analysis revealed that factors that influence farmers' decision to adopt soil conservation technology may not necessarily be the same as those that influence farmers' choice on the extent of adoption or intensity of involvement. Farmers' decision to adopt marker-ridging technology was primarily influenced by knowledge and age of the household head, labour availability and level of erosion currently taking place in the farmers' field. On the other hand, key factors influencing the extent of adoption were mainly those affecting profitability at the farm level, such as output level (yield), land size, labour availability and production assets owned by the household. Noteworthy, some factors such as knowledge of the farmer and labour availability were found to be influential at both levels of decision-making i.e., adoption and extent of adoption. Computation of marginal effects in such instance would be useful as it indicates level of influence of the variable on particular decision.

In conclusion, policy prescriptions on soil conservation should, therefore, be guided by the goals the government wants to achieve i.e., whether it wants to persuade more farmers to participate in soil conservation or to encourage those farmers already participating in the technology intensify their involvement by *inter alia* increasing land or labour allocated to soil conservation. Without any meaningful increase in the number of smallholder farmers adopting soil conservation and, willingness to intensify use of these technologies, soil erosion would continue to undermine agricultural production in Malawi leading to serious food shortage. Smallholder households are the outright losers in the long-run since most of them cannot afford to purchase other soil fertility enhancing inputs such as inorganic fertilizers.

CHAPTER VIII

SUMMARY, CONCLUSIONS AND IMPLICATIONS FOR POLICY AND RESEARCH

This study considered and empirically modelled the inter-temporal nature and dynamic costs associated with the use of soil, which are typically ignored in the literature. Most studies on soil degradation done in Africa have dwelled much on static approaches, which do not treat soil in the perspective of resource extraction (optimal resource management). Another important addition is the more realistic but complicating extensions to modelling soil erosion process as function of not only biophysical processes but also of farmers' management decisions in terms of allocation of economic resources such as labour and capital to conservation practices. The results of the study will be very useful for designing effective soil conservation policies and research in generating appropriate smallholder farming technologies that will be of relevance to many other situations around the developing world.

The thesis hinged on two main objectives and these were to measure the dynamic costs of soil degradation and, to determine factors that influence the incidence and extent of adoption of soil conservation technologies among smallholder farmers in Malawi. As such, two main analytical tools were employed to achieve the objectives stated above.

First, to measure the dynamic costs of soil degradation the study used a dynamic optimisation approach to derive and analyse the optimal conditions for soil resource extraction and use in Malawi. Secondly, a selective tobit model employing the maximum likelihood estimation (MLE) was used to determine factors influencing incidence and extent of adoption of soil conservation techniques among smallholder farmers in Malawi.

The estimated optimal control model was used to solve for SS optimal levels of the control variables of the smallholder maize farmer decision problem including SS optimal stock of soil nutrient S and dynamic price (user cost of soil quality) λ. Dynamic optima at SS were then compared to the static solutions and actual farmers' practices to evaluate the optimality of farmers' decisions with respect to sustainable use of their soil resources.

Some key findings emerged from the two analyses and relevant policy implications were also drawn in line with these findings.

The study estimated current user cost of US$21 per hectare for the smallholder farmers using the current practices. User costs represents annual loss in productive value of land. Based on this value and the total smallholder land area, economic costs of soil degradation among smallholder farmers in Malawi were estimated to amount to 14 per cent of the agricultural GDP. This figure is slightly higher compared to the one estimated by Bishop (1992). Bishop's estimations were based on static methods, which usually ignore the dynamic costs of soil use. This higher percentage may also suggest that soil degradation has accelerated over the period.

On the SS optimal path for soil resource management, the study estimated 49 kg/ha as nitrogen fertiliser rate and an optimal maize yield of 1.5ton/ha. The SS estimated optimal level of fertiliser was based on the incorporation of soil conservation management. In one of the most detailed work on fertiliser use efficiency in Malawi, Itimu (1997) indicated that 60 kgN/ha can raise 2.5 ton of maize yield and that the fertiliser amount can be halved to 30kgN/ha with use of organic manure. On average, 35kgN/ha is recommended for smallholder farmers. Estimates in the current study are slightly higher due to the fact that an inter-temporal framework, which considered the dynamic costs of soil nutrient extraction, was used. Results from fertiliser recommendation trials may be reinforced if researchers consider the inter-temporal nature and dynamic costs associated with the use of soil.

Although not operating on the SS optimal path in terms of soil resource management, current practices show that smallholder farmers in Malawi still consider, to certain degree, the dynamic costs in soil resource use. Hence, there is no strong evidence to suggest that current trends in land degradation are due to an institution failure (i.e., smallholder farmers have private incentives to conserve their soil resource). A result that suggests presence of other factors, most likely market distortions, behind existing deviations of farmers' practices from dynamic optimum.

Since smallholder farmers in Malawi have private incentives to conserve their land government policies that aim to assist these farmers operate close to the SS optimum are key not only to unlock the potential that exist in this sub-sector but also, achieve sustainable agricultural development. The government, in close partnership with the private sector, should strongly support and strengthen reforms in the input and output markets. Market competition is crucial to achieving competitive input and output prices. Improvement in the market and road infrastructure is also vital to facilitate timely distribution and access to the vital inputs by smallholder farmers. Government's serious support of the input and output market reforms is important not only to make the markets work but also, to make smallholder agriculture a profitable enterprise. It is only when smallholder agriculture becomes profitable that farmers can seriously invest in the soil resource.

The sensitivity analysis indicated that increasing the discount rate to 5%, SS solutions were close to smallholder current practice solutions. This suggests that another reason smallholder farmers are over-exploiting the soil resource is because they have a higher time preference. The high levels of poverty, especially among the smallholder subsistence farmers in Malawi, suggest that farming households are more concerned with their current survival than their future well-being.

Poor farming households (food insecure) in Malawi usually sell their labour to other households at critical times for land preparations. Agricultural support programs by government, donor communities and other non-governmental organisations that provide safety nets for the poor households should be strengthened. Such programs as "food for work", if extended to target land conservation would be vital in curtailing soil erosion among smallholder farmers. These programs also include the targeted input program (TIP)[23] proving agricultural inputs to poor smallholder farmers.

Although input subsidy policies put huge financial burden on the government, if properly managed could play a vital role in reducing land degradation (nutrient depletion) among the smallholder farmers in Malawi. Justification for such seemingly expensive interventions should be based on weighing the future consequences to the economy for not doing anything

[23] TIP is government/donor program for free distribution of inputs targeting the most vulnerable group.

now to counter the growing problem of soil nutrient stock depletion. For example, the estimated annual loss in productive land value of US$21 per hectare translates to a total loss of about US$41 million from the smallholder sub-sector alone. Subsidizing these farmers would save millions of dollars that are being lost through nutrient depletion and consequently, declining soil productivity. If left unabated, soil degradation seriously threatens not only the future of smallholder agriculture in Malawi, but any prospects of economic growth for the entire nation as well.

Results of the selective model revealed that factors that influence farmers' decision to adopt soil conservation technology may not necessarily be the same as those that influence subsequent decision on levels of adoption. For example, farmers' decision to adopt marker-ridging technology was primarily influenced by knowledge and age of the household head, labour availability and level of erosion currently taking place in the farmers' field. On the other hand, key factors influencing the extent of adoption were mainly those affecting profitability at the farm level, such as output level (yield), land size, labour availability and production assets owned by the household.

The implication of these findings is that different policy prescriptions on soil conservation should strictly be guided by the goals the government wants to achieve. For example, the government may want to persuade more smallholder farmers to participate in soil conservation or alternatively the goal of the government would be to encourage farmers already using the technology to intensify their involvement. Small-scale soil conservation techniques, due to their relative affordability and effectiveness, are regarded as one of the best options for smallholder farmers to limit the damage caused by soil erosion on the soil nutrient base. However, policies regarding adoption of soil conservation technologies would only succeed if the various needs of smallholder farmers at these two decision stages are properly identified and incorporated/addressed.

Without any meaningful increase in the number of smallholder farmers adopting soil conservation technologies and, willingness to intensify the use of the technologies, soil erosion would continue to undermine productivity of the soils in Malawi leading to serious food shortage. Noteworthy, failure to curtail soil degradation would mostly harm smallholder farmers in the long-run since most of them cannot afford to purchase other soil fertility enhancing inputs such as in organic fertilizers.

Since the study relied heavily on country average data in modelling the soil degradation problem, results based on agro-ecological zones would provide some interesting insights. Severe soil erosion taking place in other parts of the country destroys the soil physical structures. Estimations of economic costs of soil degradation can improve if effects of destruction of the soil physical structures of soils due to soil erosion were considered (i.e., incorporation of soil as an exhaustible resource).