CHAPTER IV: STUDY APPROACH TO MODELLING THE DYNAMICS OF SOIL EROSION AND SOIL NUTRIENT MINING

This chapter presents the study approach for modeling the dynamics of optimal use and extraction of the soil capital in Ethiopia. The first section presents the analytical framework adopted. Section two, offers an assessment of the nature of soil degradation problem and soil management practices in the Ethiopian highlands. Section three provides the basic assumptions used for developing the optimal control model; outlines the functional relationships between crop production and the dynamics of the stock of soil depth and soil nutrients; describes the analytical solutions of the optimal control problem and interprets the first order conditions. The last section explains input substitution possibilities required to attain dynamic optimality in the use of soil resources.

4.1 The analytical framework

The pervious chapters have ascertained that all economic analysis of soil erosion presupposes that agricultural land use removes nutrients from the land thus lowering its quality and reducing its productivity over time. Soil quality is, therefore, dynamic and continuously subject to both natural and human induced factors. Optimal soil management thus entails careful weighing current costs and benefits from actions taken today with the future costs and benefits. Barbier (1995) noted that investments in soil conservation could be considered as a redistribution of resource use rates towards the future whereas depletion implies a redistribution of resource use rates towards the present. Hence, static optimization models are not appropriate for modeling the long-term effects of soil degradation and soil conservation. This study, therefore, uses a dynamic approach to model the optimal use and extraction of soil capital.

Assuming that smallholder farmers maximize the sum of discounted future net benefits from the use of soil quality, the dynamic optimization framework is specified as:

$$Max\prod_t = \int_0^\infty e^{-\delta t}(P_tY_t - C_t(Y_t)dt \qquad (4.1)$$

In equation (4.1) π_t is the net benefit, Y_t is crop output level, P_t is the corresponding unit crop price and C_t is cost of producing output Y at time t. Input and output prices received by smallholder farmers are assumed to be exogenously determined and the discount rate, δ, reflects the time preference of smallholder farmers, which consists of pure time preference and the marginal opportunity cost of capital.

As has been discussed in the review chapter of the thesis, most previous studies that modeled the long-term impact of soil quality decline have not made a distinction between soil degradation resulting from topsoil loss (irreversible soil physical degradation) and soil degradation due to nutrient mining (reversible decline in soil quality). Consequently, most previous studies lumped both dimensions of soil degradation into one category, soil quality decline (McConnel, 1983; Saliba, 1985; LaFrance, 1992; Hoag, 1998; Hediger, 2003). However, Brekke et al. (1999) considered both sources of soil degradation but did not include conservation efforts in their analysis. A recent study by Nakhumwa (2004) included soil conservation efforts as a decision variable but focused on the reversible feature of soil degradation. Furthermore, despite the fact that smallholder farmers manage several spatially scattered plots of land exhibiting marked variability in terms of soil quality, previous modeling attempts considered soil quality to be homogeneous over all plots.

Analysis of the optimal use and extraction path of the soil capital thus requires knowledge of the major causes of soil quality decline, the conditions under which soil quality regenerates or declines and their interaction with management. Indeed, attempts to establish the conditions under which optimal use of the soil capital should occur have encountered serious methodological problems (Bishop, 1995). These methodological problems primarily stem from lack of information on the one hand and the complex relationship characterizing soil degradation and productivity on the other.

4.2 The nature of soil degradation problem and smallholder soil management practices in the highlands of Ethiopia

As has been pointed out earlier, the combination of soil nutrient mining through harvested crop biomass and water-induced loss of topsoil is responsible for soil quality decline in the Ethiopian highlands. Annual soil loss induced by soil erosion from arable lands is estimated to be very high in some locations reaching over 100 tons/ha (FAO, 1999). Also, loss of soil nutrients removed along with soil transported by water and in harvested biomass (grain and straw) is one of the highest in SSA (FAO, 1999). What makes this worse is the fact that the rate of nutrient replenishment is inadequate to offset nutrient losses as cash-constrained smallholder farmers lack the financial means to purchase commercial fertilizers in time and the right quantity (Makken, 1993; Yirga et al., 1996; Demeke et al., 1997; Adugna and Demeke, 2000). Furthermore, the traditional soil fertility management practices of long term fallowing, manure use and crop rotations involving legume crops, which were considered adequate to sustain soil fertility under low population densities, have considerably declined due to population pressure and land shortages in the highlands of Ethiopia (Tanner et al., 1992; Yirga and Hassena, 2001).

In Ethiopia, smallholder subsistence farmers manage several small plots of land scattered across a topo-sequnce or agro-ecology (Shiferaw and Holden, 1998; Yirga et al., 1998; Bekele, 2003). These plots generally differ in soil types, fertility levels, degree of slope and other plot specific features. Group discussion with smallholder farmers in the study area revealed that smallholder farmers recognize three soil depth classes: shallow (less than than 30 cm), deep (31-50) and very deep (above 50 cm); three soil fertility levels (fertile, medium and poor); and three slope classes (flat, medium and high). Accordingly, farmers' plots of land could broadly be classified into four soil quality classes depending on slope, soil depth, distance from residences and farmer perceptions:

1. Plots on flat and bottomlands. Plots under this category often referred to locally as *meda* (having a slope of less than 10%) are situated on flat to slightly undulating

bottomlands in the mid highlands (areas between 2000 and 2800 meters) and extensive plateaus in the upper highlands (areas above 2800 meters). They are generally considered to have reasonable topsoil depth (medium to high), high to medium soil fertility and less vulnerable to water induced erosion. However, these plots suffer from nutrient mining due to continuous cropping and the disruption of traditional soil fertility management practices. In most of the upper highlands irrespective of soil type and the mid highlands where vertisols predominate the problem of declining soil fertility is further complicated by poor drainage (water logging). Consequently, smallholder farmers' are concerned more about improving drainage and soil fertility than soil conservation. The most common soil fertility management practices used on this category of plots include crop rotations involving cereals, legumes and oil seeds and application of moderate levels of commercial fertilizers in the mid highlands whereas seasonal fallowing locally known as *chiflik or wortab*[7] and the use of manure and soil burning (locally known as *guie*[8]) are common in the upper highlands.

2. Plots on gentle slopes (lying between 11% and 20% slope). Plots under this category locally known as *tedafat* pertain to soils with high inherent fertility (medium to very deep top soil), naturally well drained and less susceptible to frost but vulnerable to water induced soil loss due to their undulating topography. These plots are intensively cultivated and receive priority in terms of soil fertility management and soil conservation efforts. Nonetheless, these plots, being the most intensively cultivated due to their natural fertility and better natural drainage, suffer from both nutrient mining and water erosion induced soil loss.

[7] *Chiflik* or *worteba* is a traditional soil fertility management practice in which part of a certain piece of land is fallowed for one season and used for crop production the following season. Most often the first plowing for these plots starts at the end of the main rainy season (end of August to October) immediately after the soil moisture has receded to an acceptable level.

[8] *Guie* involves plowing plots of land fallowed for over 7 years more intensively (5 to 6 times during the dry season before planting), collecting the sod into heaps and burning the soil with cow dung for barley production. Farmers claim that the practice increases soil fertility and improves drainage. Barley yields in the first year are reported to be high but decline substantially in subsequent years. This practice once important in the upper highlands is declining due to population induced land shortages.

The most common soil fertility management practices used on these plots include: crop rotations, manure and moderate levels of chemical fertilizers.

3. Plots on steep slops (lying above 21% slope). These plots locally known as *dagat* with a slope of 21% – 40% and *areh* or *gedal* with a slope of over 41% are located on the upper parts of hillsides and mountains in both the mid and upper highlands. They are generally shallow, less productive compared to plots in the other categories and highly susceptible to both water erosion and nutrient mining. Besides, in the upper highlands frost poses a considerable threat to crop production. Consequently, these plots fall low in the priority list of smallholder farmers in terms of receiving soil fertility management practices required for their sustainable utilization. However, these plots have been the main target of public soil and water conservation interventions across the highlands. Soil fertility management practices on this category of plots include crop rotations in the mid highlands and seasonal fallowing in the upper highlands.

4. Plots around homesteads. These plots locally referred to as *kossi* or a*reda* are in most instances situated adjacent to farmers' residences or a short distance from villages irrespective of landform or slope. These plots are relatively fertile due to availability of manure and other domestic wastes compared to plots located far from homesteads. Such plots being rich with organic matter due to repeated application of manure are usually planted to crops and crop varieties that require high soil fertility and as the same time contribute most to a household's food security objective (for instance false banana locally known as enset and potato), maize, faba bean and six-rowed barley varieties depending on agro-ecology. Plots in this category have the least soil degradation problem for they receive priority in terms of soil fertility management and soil conservation efforts for two reasons. First, because of location effect (backyard or a short distance from residences) they are easy to manage. Most importantly, being attached to farmers' residences or a short distance thereof, such plots are low risk investments as the chance of loosing these plots is minimal in the event of land redistribution.

Soil conservation practices used in the highlands include traditional ditches (*boyi*), cut-off drains (*golenta*), stone and soil bunds, check-dams (*kiter*) and grass-strips. The importance and intensity of use of these physical soil conservation structures, however, vary widely across agro-ecologies and locations within agro-ecologies. For instance traditional ditches, simple drainage furrows constructed manually or by the traditional oxen drawn plow for removing excess water from a plot are used across all agro-ecologies and landforms except in extreme sloping plots whereas the use of other structures is area specific.

As pointed out above, both water induced topsoil loss and nutrient mining are important in the Ethiopian highlands. Hence, spatial heterogeneity of plots are key in understanding smallholder farmers' adoption of soil conservation methods as well as in modeling the dynamics of soil use and extraction in the Ethiopian highlands.

Considering the fact that both nutrient mining and water induced topsoil losses are important in the highlands of Ethiopia and that smallholder farmers cultivate several spatially scattered and heterogonous plots of land receiving different management, the optimal control model specified below incorporates not only both dimensions of soil degradation but also the spatial heterogeneity of plots cultivated by smallholder farmers.

4.3 Modeling agricultural output, soil erosion and nutrient mining

In this section a farm level optimal control model that links changes in soil quality stock, crop production practices and soil conservation efforts is developed.

The control model developed for optimal soil extraction and use in the highlands of Ethiopia assumes the following:

1. In the highlands of Ethiopia, both water induced soil physical degradation and nutrient mining are important and occur in different intensities within and across

locations. Soil quality (Q) of a plot of land is thus a function of topsoil depth (SD) and soil nutrient stock (N) at each point in time:

$$Q_t = Q(SD_t, N_t) \tag{4.2}$$

2. The four categories of plots recognized by farmers could further be classified into two broad soil quality classes depending on observed severity of soil degradation.

i. Plots mainly suffering from nutrient mining ($\partial Q/\partial SD \approx 0$ but $\partial Q/\partial N > 0$). This scenario pertains to plots in category one and four in section 4.2.

ii. Plots susceptible to both nutrient mining and erosion ($\partial Q/\partial SD > 0$ and $\partial Q/\partial N > 0$). This scenario in the Ethiopian highlands refers to the intensively cultivated and well-drained plots of land often located on undulating topography (*tedafat*) and the marginal plots situated on slopping lands (*dagat* and *areh*), which are highly vulnerable to erosion by virtue of their location.

3. Use of moderate levels of commercial fertilizers, manure application on selected plots of land and seasonal fallowing represent the main soil fertility management practices of smallholders in the highlands of Ethiopia.

4. Smallholder crop production in the mixed crop-livestock farming systems of the highlands involves intensive use of family labour with very little external inputs. Land preparation is mainly done by oxen drawn local plough. Availability of a team (pair) of oxen and adult male labour among other things determines timely land preparation and planting, as well as the type and mix of crops planted by a household in any one season, which in turn determines crop productivity. Most farmers use local crop varieties and seeds from own harvest. The major agricultural operations such as land preparation, weeding and harvesting are accomplished mainly by family labour. Indeed, ownership of a team of oxen, adequate seed

reserves from own harvest and availability of family labour constitute the major farming inputs of smallholder farming in the highlands.

5. Like elsewhere in SSA, labor input with very little capital constitute the soil conservation effort in the highlands of Ethiopia.

Following Saliba (1985) and drawing on the work of Nakhumwa (2004) a yield function relating output to soil characteristics and management variables is specified. Production (Y_t) per hectare (ha) of arable land at time t is defined as a function of topsoil depth (SD_t), stock of soil nutrients (N_t), two productive inputs labor (L_{Yt}), and capital[9] (K_{Yt}). The production function (time subscripts suppressed) is given by:

$$Y = f(L_Y, K_Y, SD, N) \tag{4.3}$$

The production function (f) is assumed to have all the properties of a well-behaved production function (twice continuously differentiable and increasing with soil depth and soil nutrient stock). As indicated by Nakhumwa (2004), in this formulation fertilizer inputs (F) is specified to directly augment the soil nutrient pool but influence output indirectly via the stock of soil nutrients (N) as plants for their growth and development use nutrients from the nutrient pool in the soil.

Soil depth and stock of soil nutrients are the state variables both of which constitute the farmers capital. While soil depth is assumed to represent the irreversible productivity effects of physical degradation, stock of soil nutrients represent the reversible aspect of soil quality decline (soil nutrient mining).

Nakhumwa (2004) modeled the reversible aspect of soil degradation for Malawi. This study focusing on both dimensions of soil degradation (the irreversible soil physical degradation and the reversible decline in soil quality) extends Nakhumwa's (2004)

[9] Capital for production in this study refers to two critical inputs: the services of a pair of oxen which could be owned by a household, solicited from fellow farmers through cash rentals, exchange for labor services, livestock feed or other social arrangements and soil resources.

specification incorporating a state variable depicting the inter-temporal dynamics of soil depth, which is assumed to represent the physical aspect of soil degradation.

The time rate of change of soil depth depends on the natural soil regeneration and degradation process as well as the rate of topsoil loss due to cultivation as follows:

$$\dot{SD} = H(Z, L_S, Y) \tag{4.4}$$

In equation (4.4) $\dot{SD}$ denotes the inter-temporal change of the soil depth at time t as a function of the natural soil regeneration and damage (Z), conservation labor input (L_S) and cultivation intensity (Y). The canopy of output, Y, by reducing the kinetic energy of raindrops hitting the soil surface deters (lowers) erosion, which consequently reduces nutrient loss. Similarly, soil conservation efforts through labor input (L_S) by reducing soil decay further contribute to minimizing nutrient decay. The function (H) above, therefore, implies that smallholder farmers can manipulate erosion rates by varying conservation effort and/or by influencing yields (canopy) via the control variable in the optimization problem.

The dynamics of the soil nutrient stocks is governed by three processes: fertilizer inputs G(F) in the form of organic and inorganic nutrients, nutrient removal through crop harvest D(Y) and nutrient build up and decay due to natural soil formation processes and nutrient loss along with eroded soil (H). Following Nakhumwa (2004), the time rate of change of the soil nutrient stock is specified as:

$$\dot{N} = G(F) - D(Y) + M(\dot{SD}) \tag{4.5}$$

Substituting equation (4.4) into equation (4.5),

$$\dot{N} = G(F) - D(Y) + M(Z, L_S, Y) \tag{4.6}$$

In equations (4.5 and 4.6) $\dot{N}$ denotes the inter-temporal evolution of the stock of soil nutrients where, G(F) is a nutrient augmentation function through external supply of organic and inorganic fertilizers; D(Y) is a nutrient damage function through output harvest (grain and straw); *M* denotes an aggregate nutrient decay and regeneration function associated with the aggregate soil loss function in equation (4.4).

4.3.1 The optimal nutrient mining and soil erosion control model

As has been shown above smallholder farmers are assumed to maximize the sum of discounted net returns over the planning horizon by choosing levels of fertilizer use (F), labor (L_Y), capital (K_Y) inputs for production and amount of soil conservation effort through the choice of labor (L_S) input. Incorporating the production function (equation 4.3), the dynamics of the soil depth (equation 4.4) and the stock of soil nutrients (equation 4.6) into the conceptual framework (equation 1), the optimal control problem for a given area of land then becomes the maximization of the discounted sum of the stream of net benefits (Π) from soil use with an infinite time given as (time subscripts suppressed):

$$Max \prod_{F, L_Y, K_Y, L_S} = \int_0^{\infty} e^{-\delta t}[Pf(L_Y, K_Y, SD, N) - (W_F F + W_L L_Y + W_S L_S + W_K K_Y)]dt \quad (4.7)$$

Subject to equations of motion and initial conditions:

$$\dot{SD} = H(Z, L_S, Y) \quad (4.8)$$

$$\dot{N} = G(F) - D(Y) + M(Z, L_S, Y) \quad (4.9)$$

$$SD(0) = SD_0 \quad (4.10)$$

$$N(0) = N_0 \quad (4.11)$$

where P denote the price of output, δ, W_F, W_L, W_S and W_K denotes the rate of discount, the unit costs of fertilizer, labor for production and conservation and capital for production inputs, respectively.

Analytical solutions of this control problem are based on the following assumptions about first and second order partial derivatives.

1. Output increases with labor (L_Y) and capital (K_Y) use in cultivation, soil depth (SD) and stock of soil nutrients (N) given by

$$\frac{\partial f}{\partial L_Y} > 0, \frac{\partial f}{\partial K_Y} > 0, \frac{\partial f}{\partial SD} > 0, \frac{\partial f}{\partial N} > 0, \frac{\partial^2 f}{\partial L_Y^2} < 0, \frac{\partial^2 f}{\partial K_Y^2} < 0, \frac{\partial^2 f}{\partial SD^2} < 0, \frac{\partial^2 f}{\partial N^2} < 0,$$

2. Increase in soil conservation effort, use of labor (L_S) reduces erosion damage (reduce soil loss) and hence increase or maintain soil depth, $\partial H / \partial L_S \geq 0$;
3. Increase in cultivation intensity, defined as intensive use of labor (L_Y) and capital (K_Y) for cultivation is assumed to increase output. Higher output levels as a result of better crop cover (enhanced canopy) reduce soil damage and hence maintain or enhance soil depth, $\partial H / \partial L_Y = H_{L_Y} \geq 0$ and $\partial H / \partial K_Y = H_{K_Y} \geq 0$;
4. Soil loss due to erosion decreases with increased stock of soil depth (soil depth effect on canopy), $\frac{\partial H}{\partial SD} = \frac{\partial H}{\partial Y} \frac{\partial Y}{\partial SD} = H_{SD} \geq 0$;
5. Soil loss decreases with nutrient stock (nutrient stock effect on canopy), $\frac{\partial H}{\partial N} = \frac{\partial H}{\partial Y} \frac{\partial Y}{\partial N} = H_N \geq 0$;
6. Soil conservation effort through its effect of reducing erosion damage reduces nutrient decay, $\partial M / \partial L_S \leq 0$;
7. Fertilizer application augments soil nutrient stocks, $\partial G / \partial F > 0$;
8. Cultivation intensity (intensive use of labor and capital for production) by improving yield aggravates nutrient damage, $\partial D / \partial L_Y = D_{L_Y} \geq 0$ and $\partial D / \partial K_Y = D_{K_Y} \geq 0$ while improved canopy reduces nutrient decay, $\partial M / \partial L_Y = M_{L_Y} \leq 0$ and $\partial M / \partial K_Y = M_{K_Y} \leq 0$;

The Hamiltonian for this maximization problem is:

$$\Pi(F, L_Y, K_Y, L_S, SD, \mathrm{N}, \lambda, \mu) = e^{-\delta t}\left[Pf(L_Y, K_Y, SD, N) - (W_F F + W_L L_Y + W_S L_S + W_K K_Y)\right] + \lambda\left[H(Z, L_S, Y)\right] + \mu\left[G(F) - D(Y) + M(Z, L_S, Y)\right] \tag{4.12}$$

The FOC for this system:

$$\frac{\partial \Pi}{\partial F} = -e^{-\delta t}W_F + \mu\frac{\partial G}{\partial F} = 0 \Rightarrow e^{\delta t}W_F = \mu\frac{\partial G}{\partial F} \tag{4.13}$$

$$\frac{\partial \Pi}{\partial L_Y} = e^{-\delta t}P\frac{\partial f}{\partial L_Y} - e^{\delta t}W_L + \lambda\frac{\partial H}{\partial L_Y} - \mu\frac{\partial D}{\partial L_Y} + \mu\frac{\partial M}{\partial L_Y} = 0 \tag{4.14a}$$

$$e^{-\delta t}\left(Pf_{L_Y} - W_L\right) = -\lambda H_{L_Y} + \mu\left(D_{L_Y} - M_{L_Y}\right) \tag{4.14b}$$

$$\frac{\partial \Pi}{\partial K_Y} = e^{-\delta t}P\frac{\partial f}{\partial K_Y} - e^{\delta t}W_K + \lambda\frac{\partial H}{\partial K_Y} - \mu\frac{\partial D}{\partial K_Y} + \mu\frac{\partial M}{\partial K_Y} = 0 \tag{4.15a}$$

$$e^{-\delta t}\left(Pf_{K_Y} - W_K\right) = -\lambda H_{K_Y} + \mu\left(D_{K_Y} - M_{K_Y}\right) \tag{4.15b}$$

$$\frac{\partial \Pi}{\partial L_S} = -e^{-\delta t}W_S + \lambda\frac{\partial H}{\partial L_S} + \mu\frac{\partial M}{\partial L_S} = 0 \tag{4.16a}$$

$$e^{-\delta t}W_S = \lambda H_{L_S} + \mu M_{L_S} \tag{4.16b}$$

$$\dot{\lambda} = -e^{-\delta t}\frac{\partial \Pi}{\partial SD} = -e^{-\delta t}P\frac{\partial f}{\partial SD} - \lambda\frac{\partial H}{\partial SD} + \mu\left(\frac{\partial D}{\partial SD} - \frac{\partial M}{\partial SD}\right) \tag{4.17}$$

$$\dot{\mu} = -e^{-\delta t}\frac{\partial \Pi}{\partial N} = -e^{-\delta t}P\frac{\partial f}{\partial N} - \lambda\frac{\partial H}{\partial N} + \mu\left(\frac{\partial D}{\partial N} - \frac{\partial M}{\partial N}\right) \tag{4.18}$$

$$\frac{\partial \Pi}{\partial \lambda} = \dot{SD} = Z - E + J \tag{4.19}$$

$$\frac{\partial \Pi}{\partial \mu} = \dot{N} = G(F) - D(Y) + M(Z, L_S, Y) \tag{4.20}$$

4.3.2 Interpreting the first order conditions (FOCs)

The equations (4.13-4.18) shown above represent the first order conditions governing the inter-temporal optimal use and extraction of soil capital in the highlands of Ethiopia. Scenario specific FOCs derived on the assumption of heterogeneous soil quality shown on section 4.3 are summarized in table 4.1. The analytical results assert that the optimal inter-temporal use and extraction paths corresponding to the two soil degradation scenarios differ considerably.

Equation (4.13) describes optimal use of fertilizer by balancing short-term costs against long-term benefits. In both scenarios fertilizer should be used until the discounted unit price of fertilizer $(e^{-\delta t} W_F)$ equals the marginal contribution of an extra unit of fertilizer to the stock of soil nutrients (μG_F). The latter is the product of the dynamic price of nutrient stock and the marginal contribution of one unit of fertilizer to soil nutrient stock (Table 4.1, row F).

Equation (4.14) describes the optimal condition of labor use in cultivation. It states that labor in cultivation should be used up to the point where the discounted net marginal value $[e^{-\delta t}(Pf_{L_Y} - W_{L_Y})]$ equals the net marginal contribution to soil quality or equivalently to the net dynamic benefit from the use of soil quality for production. However, the dynamic benefit of an extra unit of labor used in cultivation differs for the two soil degradation scenarios (Table 4.1, row L_Y). In scenario I, the dynamic benefit constitutes the net marginal value of soil nutrient stocks saved $[\mu(D_{L_Y} - M_{L_Y})]$ due to the use of one extra unit of labor in cultivation. The net marginal benefit in this scenario consists of three terms. The first term is the dynamic price of soil nutrient stock; the second term represents the marginal nutrient loss due to higher output achieved (the marginal increase in nutrient damage function) while the last term denotes the marginal reduction in nutrient decay (nutrient saved) due to better canopy. In scenario II, since the use of labor in production affects both dimensions of soil degradation (soil physical destruction and nutrient mining) the social benefit includes the sum of the marginal reduction of physical degradation $(-\lambda H_{L_Y})$ and the net marginal reduction of soil nutrient decay due to crop harvest and canopy, $[\mu(D_{L_Y} - M_{L_Y})]$, as a result of using one unit of labor in cultivation.

The optimal condition of capital use in cultivation is provided by equation (4.15). A similar interpretation to that of labor for production applies. It states that capital in cultivation should be used up to the point where the discounted net marginal value $[e^{-\delta t}(Pf_{K_Y} - W_{K_Y})]$ equals the net marginal contribution to soil quality or equivalently to the net dynamic benefit (Table 4.1, row K_Y).

Equations (4.16a and 4.16b) describe the first order optimal conditions of conservation effort. At the optimum, labor for soil conservation should be used until the discounted wage rate $(e^{-\delta t}W_{L_S})$ equals the marginal value contributions of one unit of labor to soil quality. In other words, labor for soil conservation should be used to the point where the discounted unit cost of labor equals the long-term marginal benefit expected from the marginal reduction in soil decay. In scenario I, the marginal value contribution constitutes the dynamic price of soil nutrient stock multiplied by the marginal contribution of soil nutrient stock saved, (μM_{L_S}) as a result of using one unit of labor in soil conservation. Similarly, in scenario II, the marginal value contribution of labor used in soil conservation consists of the sum of the marginal value contributions of soil depth and soil nutrients saved by an extra unit of labor used in soil conservation effort denoted by $(\mu M_{L_S} + \lambda H_{L_S})$ (Table 4.1, row L_S).

Finally, equations (4.17) and (4.18) determine the adjustment in the rate of change of the shadow price of soil depth $(\dot{\lambda})$ and soil nutrient stock $(\dot{\mu})$ along the optimal path. In scenario I, the shadow value of soil nutrient stock declines (appreciates) at the rate at which soil nutrient stock contributes to the current profits $(e^{-\delta t}Pf_N)$ plus the sum of the marginal contribution of soil nutrient stock to nutrient decay through crop harvest and build up through canopy $[\mu(D_N - M_N)]$ (Table 4.1, row μ). Apparently, as the second

Table 4.1. First order optimal conditions for two soil degradation scenarios derived from the optimal control model of soil nutrient mining and physical topsoil degradation

Variable	Major sources of soil quality decline	
	Soil nutrient mining only	Physical soil degradation and soil mining
	$(\mu > 0)$ & $(\lambda = 0)$	$(\mu > 0)$ & $(\lambda > 0)$.
F	$e^{-\delta t} W_F = \mu G_F$	$e^{-\delta t} W_F = \mu G_F$
L_Y	$e^{-\delta t}(Pf_{L_Y} - W_L) = \mu(D_{L_Y} + M_{L_Y})$	$e^{-\delta t}(Pf_{L_Y} - W_L) = -\lambda H_{L_Y} + \mu(D_{L_Y} - M_{L_Y})$
K_Y	$e^{-\delta t}(Pf_{K_Y} - W_{K_Y}) = \mu(D_{K_Y} + M_{K_Y})$	$e^{-\delta t}(Pf_{K_Y} - W_{K_Y}) = -\lambda H_{K_Y} + \mu(D_{K_Y} - M_{K_Y})$
L_S	$e^{-\delta t} W_L = \mu M_{L_S}$	$e^{-\delta t} W_L = \mu M_{L_S} + \lambda H_{L_S}$
λ	N.A.	$\dot{\lambda} = -e^{-\delta t} P \frac{\partial f}{SD} - \lambda \frac{\partial H}{\partial SD} + \mu(\frac{\partial D}{\partial SD} - \frac{\partial M}{\partial SD})$
μ	$\dot{\mu} = -e^{-\delta t} P \frac{\partial f}{\partial N} + \mu(\frac{\partial D}{\partial N} - \frac{\partial M}{\partial N})$	$\dot{\mu} = -e^{-\delta t} P \frac{\partial f}{\partial N} - \lambda \frac{\partial H}{\partial N} + \mu(\frac{\partial D}{\partial N} - \frac{\partial M}{\partial N})$

N.A.= Note applicable

scenario considers both dimensions of soil degradation, the system of FOCs consists of both the shadow price of soil depth (λ) and soil nutrient stock (μ). In the second scenario, the rate of change of the shadow value of the stock of soil depth $(\dot{\lambda})$ or the shadow price of soil quality attributed to the use of one unit of soil depth at the present rather than having it conserved declines (appreciates) at the rate soil depth contributes to current profit $(e^{-\delta t} Pf_{SD})$ and the sum of marginal contributions of soil depth and the stock of soil nutrients $[-\lambda H_{SD} + \mu(D_{SD} - M_{SD})]$ to future profits. Similarly, the rate of change of the shadow value of soil nutrient stock $(\dot{\mu})$ or the shadow price of soil quality attributed to the use of one unit of soil nutrient stock declines at the rate soil nutrient stock contributes to the current profits $(e^{-\delta t} Pf_N)$ plus the sum of the marginal contributions of soil depth $(-\lambda H_N)$ and nutrient stock $[\mu(D_N - M_N)]$ to soil quality.

4.4 Input substitution

The first order conditions shown above suggest that farmers in the highlands of Ethiopia are unlikely to follow a single strategy to achieve dynamic optimality in the use of soil capital. The appropriate optimal decision rules given the production technology and soil resource dynamics, corresponding to the two-soil degradation scenarios are given in Table 4.2. A brief discussion follows.

The optimality rules for the allocation of labor between cultivation (L_Y) and conservation (L_S) equates the ratio of the net marginal value product of labor in cultivation to labor in conservation (LHS[10]) with the ratio of the dynamic benefits of labor in cultivation to labor in conservation (RHS[11]) (Table 4.2, row L_Y&L_S). Similarly, the optimal decision rule for the allocation of labor (L_Y) and capital (K_Y) in production is governed by equating the ratios of the net marginal value product of labor to capital in cultivation (LHS) with the dynamic benefits of labor to capital in cultivation (RHS) (Table 4.2, row L_Y&K_Y). However, it should be noted that while the LHS of the optimality rule in the two scenarios is similar, the components of the dynamic benefits at the RHS differ for the two scenarios depending on the dimension of soil quality decline considered.

The optimality rules among the allocation of fertilizer and labor (F&L_Y) and fertilizer and capital in cultivation (F&K_Y), fertilizer and labor for conservation (F&L_S) are provided in Table 4.2, rows, F&L_Y, F&K_Y, F&L_S. In the first two cases, the optimality rules involve

[10] Left hand side
[11] Right hand side

equating the ratio of the unit cost of fertilizer to the respective net marginal value products of labor to capital for cultivation (LHS) with the ratio of dynamic benefits from use of fertilizer to the dynamic benefit of labor to capital for cultivation, respectively (RHS). Similarly, the optimality rule for the allocation of fertilizer and labor for conservation involves equating the ratio of the unit costs of fertilizer to the unit cost of conservation labor (LHS) with the ratio of the dynamic benefits of fertilizer to labor in conservation (RHS).

Table 4.2. Optimality rules for resource allocation under two soil degradation scenarios

Input mix	Major sources of soil quality decline	
	Soil nutrient mining only	Physical soil degradation and soil mining
	$(\mu > 0)$, $(\lambda = 0)$	$(\mu > 0)$, $(\lambda > 0)$.
L_Y&L_S	$\frac{Pf_{L_Y} - W_{L_Y}}{W_L} = \frac{D_{L_Y} - M_{L_Y}}{M_{L_S}}$	$\frac{Pf_{L_Y} - W_{L_Y}}{W_L} = \frac{\mu(D_{L_Y} - M_{L_Y}) - \lambda H_{L_Y}}{\mu M_{L_S} + \lambda H_{L_S}}$
L_Y&K_Y	$\frac{Pf_{L_Y} - W_L}{Pf_{K_Y} - W_{K_Y}} = \frac{D_{L_Y} - M_{L_Y}}{D_{K_Y} - M_{K_Y}}$	$\frac{Pf_{L_Y} - W_L}{Pf_{K_Y} - W_K} = \frac{\mu(D_{L_Y} - M_{L_Y}) - \lambda H_{L_Y}}{\mu(D_{K_Y} - M_{K_Y}) - \lambda H_{K_Y}}$
F&L_Y	$\frac{W_F}{Pf_{L_Y} - W_{L_Y}} = \frac{G_F}{D_{L_Y} - M_{L_Y}}$	$\frac{W_F}{Pf_{L_Y} - W_{L_Y}} = \frac{\mu G_F}{\mu(D_{L_Y} - M_{L_Y}) - \lambda H_{L_Y}}$
F&K_Y	$\frac{W_F}{Pf_{K_Y} - W_{K_Y}} = \frac{G_F}{D_{K_Y} - M_{K_Y}}$	$\frac{W_F}{Pf_{K_Y} - W_{K_Y}} = \frac{\mu G_F}{\mu(D_{K_Y} - M_{K_Y}) - \lambda H_{K_Y}}$
F&L_S	$\frac{W_F}{W_L} = \frac{G_F}{M_{L_S}}$	$\frac{W_F}{W_L} = \frac{\mu G_F}{\mu M_{L_S} + \lambda H_{L_S}}$
K_Y&L_K	$\frac{Pf_{K_Y} - W_{K_Y}}{W_L} = \frac{D_{K_Y} - M_{K_Y}}{M_{L_S}}$	$\frac{Pf_{K_Y} - W_{K_Y}}{W_L} = \frac{\mu(D_{K_Y} - M_{K_Y}) - \lambda H_{K_Y}}{\mu M_{L_S} + \lambda H_{L_S}}$

Finally, the optimal decision rule for the allocation of capital for production and labor for conservation is governed by equating the ratios of the net marginal value product of capital to the unit cost of labor in conservation (LHS) with the dynamic benefits of capital in cultivation to labor in conservation (RHS) (Table 4.2, row K_Y&L_S).

CHAPTER V: STUDY AREA, SURVEY DESIGN AND SELECTED SOCIO-ECONOMIC CHARACTERISTICS OF THE SAMPLE HOUSEHOLDS

This chapter describes the study locations, the research design and socio-economic characteristics of the sample households. It begins with describing the geographical location and agro-ecological characteristics of the study area. This is then followed by a description of survey design and sampling procedures in section two. Section three provides sources and types of data collected for the empirical specification and estimation of the dynamic optimization model in chapter 6 and soil fertility and conservation adoption models in chapter 8. The last section, section four presents selected characteristics of the sample households and the production system.

5.1 The study area

The study was conducted in the highlands of Dendi and Debre Birehan Zuria districts within the Central Highlands defined as areas with an altitude range of 1,500 to 3500 meters above sea level, receiving rainfall of 900 to 1,500 mm per annum and average temperature of 18 to 25 ºC. The central highlands, though endowed with rich natural resource base and favorable climate, is undergoing serious ecological degradation because of increasing human and livestock population pressures. The central highlands were thus chosen, as the area of focus for it is believed to represent the wider highlands of the country with regard to socio-economic, demographic as well as ecological aspects. Soil fertility and soil conservation technologies were extensively promoted in the central highlands by government and NGOs as part of a broad program launched to attain food self-sufficiency and reverse soil degradation in the country.

5.1.1 Dendi district

The highlands of Dendi district, located in West Shewa zone of Oromia Region about 80-110 km west of Addis along the Addis-Ambo highway, is characterized by two dominant farming systems: the barley based crop-livestock farming systems of the upper highlands lying above 2600 meters and the tef-wheat based crop-livestock farming systems of the mid highlands lying between 2000 and 2600 meters.

The highlands of Dendi district have two rainfall seasons, the first rains known locally as *belg* falling between February to May followed by the main rainy season locally known as *kiremet* falling from June to September. Annual rainfall varies from 580 mm to 1063 with a long-term average of 879 mm as measured at Ginchi metrological station in the district town of Ginchi. Of these, about 28.1% falls during the short rainy season while the rest, 72.9% falls during the main rainy season (Figures 5.1). While the main rainy season is quite reliable, the short rains exhibit considerable variability in terms of on-set, amount and distribution. Mean monthly minimum and maximum temperatures range from 5.2 to 10ºC and 22.1 to 24.9ºC, respectively, as measured at Ginchi.

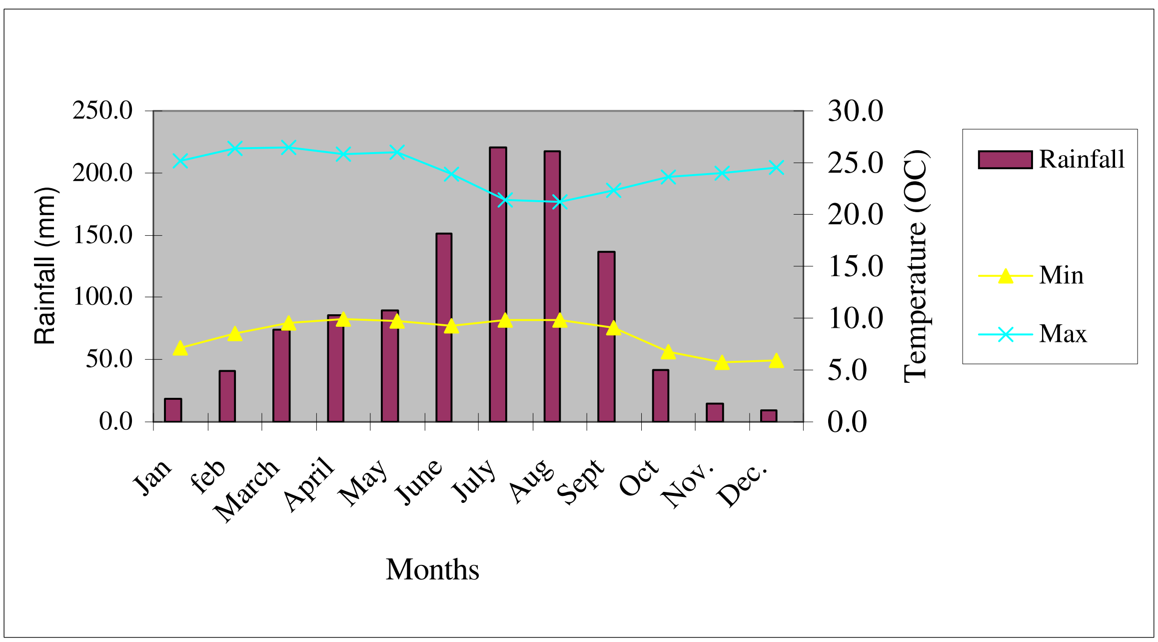

Figure 5.1. Long-term average monthly rainfall and temperature distributions at Ginchi (Dendi district), 1982-2002, Ethiopia.

Source: Holetta Research Center (unpublished data)

The soils of the mid highlands include Vertisols, Cambisols and Nitsols in their order of appearance whereas soils in the upper highlands are predominantly Nitoslols.

5.1.2 Debre Birehan Zuria district

Debre Birehan Zuria district, located in North Shewa Zone of the Amhara region at about 130-150 north of Addis Ababa along the Addis-Dessie highway, is classified as a low potential with good market access.

Annual rainfall, as measured in the district town of Debre Birehan, varies from 467mm to 1068 mm with a long-term average of 874 mm of which about 19% falls during the short rainy season while the rest, 81% falls during the main rainy season (Figures 5.2). Mean monthly minimum and maximum temperatures ranges between 4.8ºC to 7.1ºC and 19.1 to 20.5ºC, respectively. The major soil types of the area include Andosols, Regosols and Cambisols.

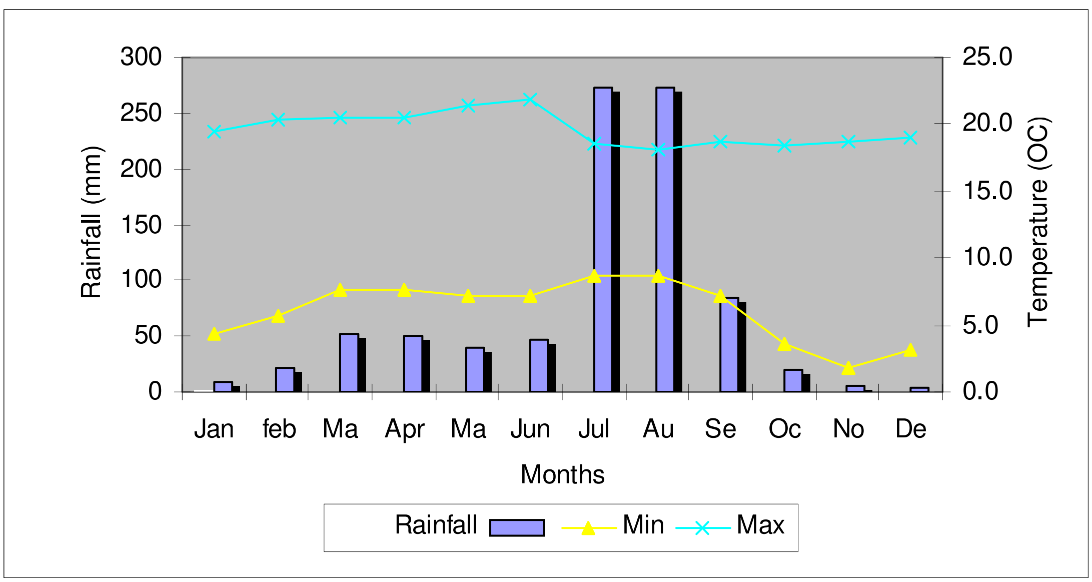

Figure 5.2. Long-term average monthly rainfall and temperature distributions at Debre Birehan, 1982-2002, Ethiopia.

Source: Sheno Research Center (Unpublished Data)

5.2 Survey design and sampling procedures

To date, availability of suitable data has been and still is the main bottleneck to a more rigorous empirical analysis of soil degradation control particularly in developing countries. In this study secondary and primary data collected in various ways were utilized to attain the objectives set in chapter one. Both secondary and primary data have their advantages and limitations. Secondary data is relatively cheap to acquire. However, it may suffer from various problems such as incomplete records, aggregation errors that are not under the control of the researcher or even may not be apparent to the researcher at all. Primary data, on the other hand, suffer less from the aforementioned limitations but are costly to undertake. Recognizing the limitations and strengths of both types of data, this study used a combination of secondary and primary data to model the dynamic costs and benefits of soil degradation control and soil fertility and conservation adoption behaviour of smallholder farmers in the study area. The study, therefore, used a combination of procedures to collect the required data: secondary data from various sources, informal surveys (individual and group discussions with farmers as well as key informants) and questionnaire based focused household surveys.

The study targeted smallholder farmers in the central highlands of Ethiopia. The study employed a multi-stage sampling procedure involving a purposive selection of regions[12], zones and districts followed by a random selection of peasant associations (PAs) within districts, and finally households from selected PAs. Within the Central Highlands, North Shewa zone from the Amhara region and West Shewa zone from the Oromia region were purposively selected to capture diversity in terms of agro-ecological representation (having both high potential and low potential zones), degree of past soil conservation effort and socio-economic differences (settlement pattern, whether or not recent land redistribution has been implemented). Following the identification of zones, two districts, one from each of the two zones namely Dendi from West Shewa zone and Debre Birehan

[12] The country is divided into 12 ethnically based regions. Each region is again sub divided into several zones, zones into districts. Districts also referred to as *woredas* are self-governing areas consisting of a number of peasant associations, which in turn form the grass root administrative units composed of several villages (gotes).

also referred to as Basona Worena district from North Shewa zone were purposively selected (Table 5.1). While Dendi district is characterized by a warmer mid highlands lying between 2000 to 2600 meters and a cooler upper highlands lying over 2600 meters, the Debre Berihan Zuria district on the other hand is predominantly characterized by cool temperate like climate lying above 2800 meters.

Table 5.1. Basic features of the study sample and the study locations

District	District		
	Debre Berihan	Dendi	
Selected PAs	Gudo Beret and Wushawushi	Legabato	Gallessa
Sample size	120	58	55
Altitude (meters)	2800-3500	2200-2600	2800-3200
Average Rainfall (mm)	874	879	N.A.
Major soil types	Regosols and Andosols	Vertisols and Cambisols	Nitosols
Topography	Rugged	Undulating to flat	Rugged
Cropping pattern	Barley and legume based	Teff and wheat based	Barley and enset based
Production seasons	Both belg and meher	Meher only	Mainly meher
Agricultural potential	Low	High	Medium
Distance to the major market	5-50	10-20	30-50
Dominant ethnic group	Amhara	Oromo	Oromo
Year last done land redistribution	1997	1984	1984
Degree of past SWC effort	High	Limited	Low

Note: N.A.= Not available; SWC=Soil and Water Conservation

Stratification at the level of a district is crucial to identify homogenous groups (strata) in order to increase accuracy of the sample estimates. To this end, the PAs in the respective districts were first grouped into two categories based on altitude, cropping pattern, degree of past efforts in soil conservation extension and proximity to the district town (access to market). Then, a total of four PAs, two from each of the districts, namely Gallessa and Lagabato from Dendi district representing the upper and mid highlands of Dendi, respectively; and Gudo Bert and Wushawushi from Debre Birehan Zuria district both in the upper highlands but differ in market access were randomly drawn from each category.

Statistical theory stresses the importance of optimal sample size for accurate estimation of the variables of interest and for subsequently testing hypotheses at the desired level of precision. Also, statistical theory asserts that precision increases at a decreasing rate with larger sample size. An optimal sample size is, therefore, determined at the point where no significant efficiency gains will result from the use of extra resources to select additional sampling units. In this study, smallholder farmers who owned land (received land from the respective PAs or inherited from their parents and therefore pay land taxes) were the sampling unit at the level of the PA. Lists of farm households were solicited from the respective PA offices, reviewed and up dated to include recent household dynamics with the assistance of the executive committee members of the respective PAs. The updated list was then used as a sampling frame[13] to draw households using a simple random sampling technique.

In this study it was not possible to determine the optimal sample size on the basis of the desired level of precision as suggested by statistical theory due to lack of reliable information[14] on estimates of the variance of a closely related variable of interest. Financial resources and research time were, therefore, dictated the sample size. Consequently, given the financial resources and available time, 10% of households from each of the selected PAs were randomly drawn and included in the survey. A total of 233

[13] The sampling frame includes households who own land and pay land taxes. Hence, landless PA residents and newly established households who received land from their parents for establishing residential houses but do not bear land titles were not included in the sampling frame as these households were neither considered as farming households or PA members.
[14] Available studies reported mean values of variables of interest but not their spread measures

households, 120 from Debre Birehan and 113 from Dendi were included in the household survey (Table 5.1). However, due to incomplete records and inconsistent information, four questionnaires were dropped making the final sample 229 households managing some 1599 plots and sub plots.

5.3 Types of data collected

Necessary data were collected from various sources including secondary sources, participatory rural appraisal (PRA) and focused formal household surveys from September to December 2003.

Secondary data were collected from various agencies including agricultural research stations, the ministry of agriculture (MOA) at various levels and the SCRP. The primary data collection included participatory rural appraisal (PRA) using non-structured discussion guidelines followed by a focused formal survey using a structured questionnaire. The PRA was aimed at collecting qualitative information from focused group discussions with farm household heads and key informant interviews. The information from the informal survey provided useful insight about the farming systems of the areas and subsequently used as a basis for questionnaire preparation, administration and conducting of the formal survey at a household level.

Following the PRA, a structured questionnaire were prepared, pre-tested and administered to a total of 233 randomly selected households. A range of data at various scales: plot, farm and household were collected. Plot level data focused on plot characteristics (plot size, distance from residence, severity of soil degradation, fertility level, perceived plot productivity, slope, etc.); crop production practices (crop type, frequency and timing of operations such as plowing, weeding, harvesting); soil fertility and soil conservation practices used during the previous and the survey years; inputs used (amount of organic and inorganic fertilizers, seed rate and chemicals); and output per unit area. Major socio-economic variables collected include demographic structure of households, farm size, livestock owned. Moreover, data on access to credit, extension and improved inputs were collected from the household survey.

5.4 Socio-economic characteristics of the study sample

Socio-economic differences including demographic structure of sample households and access to and control of key economic resources among others are presumed to be responsible for observed differential responses among smallholder farmers. As in the rest of the highlands of Ethiopia, in the study area too, family labour, land and livestock form key resources indispensable to small-scale agriculture.

In Ethiopia including the study area, land is a pubic property under the custody of the government. Farmers have use rights on the land under their management but are not allowed to sale or exchange. To start farming, therefore, a household need to have land allocated from the PA in which he/she is a member. The size of land holding a household is entitled to manage (cultivate) at the time of land allocation (redistribution) is largely a function of available land within the jurisdiction of the PA boundaries and population density.

Smallholder agriculture in the study area is also characterized by a high degree of reliance on family labour. The major agricultural operations such as land preparation, weeding and harvesting are accomplished mainly by family labour. As in all cereal based farming systems of the highlands, in the study area too, male adult labour is critical to accomplish timely land preparation using the traditional oxen drawn plough.

Another key resource indispensable to farming in the highlands is livestock. First, livestock provides draft power (tillage, threshing and transportation). Second, livestock generates cash income for the purchase of farm inputs (e.g. inorganic fertilizer) and to pay for other expenses. Third, animal manure is an important source of plant nutrients used to replenish nutrients lost through harvested biomass and along with eroded soil. Besides its importance as a source of domestic fuel for cooking, animal manure in Debre Birehan Zuria district is a valuable source of cash income as the fresh manure is made into dung cakes, dried and sold at local markets. Fourth, livestock are considered as capital investments, which could be sold to offset the uncertainties of crop production under unfavourable climate. Therefore, a household's production and consumption strategies involves tradeoffs in the use of these inputs for meeting current consumption (current production) and the maintenance and enhancement of these resources for future use. The following sub-sections provide a brief description of household, farm and plot characteristics of sample households as well as the production system of the study area.

5.4.1 Household characteristics

Family size in the study area is generally high with an average of 6 persons in Debre Birehan and 7 persons in Dendi. The average age of the sample household heads is 48 years. Illiteracy is prevalent in rural Ethiopia. About 61% of the respondents do not read and write, while 39% have some type of formal education (Table 5.2). Of the total sample households, 48% live in grass-thatched houses and 52% live in corrugated roofed houses. About 8.3% sample households were found to be female headed.

Off-farm job opportunities are generally limited in the study area. Only 24.9% of the sample households were gainfully employed in some type of off-farm activities and earn on average 549 Birr per year from occupations related to petty trade and crafts, post-harvest agriculture, causal work and other services.

5.4.2 Plot and farm characteristics

Among others, physical plot characteristics including slope, soil depth, level of soil fertility and potential productivity of a plot play a crucial role in the adoption decision of soil fertility management and soil conservation practices by smallholder farmers. Table 5.3 provides the most important plot characteristics identified by survey respondents. Of the total 1599 plots and subplots managed by the sample households in both districts about 50.9% are classified to have some level of degradation, of which 12.2%, 18.6% and 28.6% of the plots are rated to be very severely, severely and lightly degraded, respectively. Soil quality classes identified on the bases of aforementioned plot characteristics are discussed in chapter 4.

Table 5.2. Selected household characteristic of the sample households in the highlands of Dendi and Debre Birehan, Central highlands of Ethiopia, 2003

Item	Debre Birehan	Dendi	Whole sample
Family size (count)	Households (%)		
2-3	8.5	8.9	8.7
4-7	68.4	59.8	64.2
>7	23.1	31.3	27.1
Mean family size (No.)	5.86	6.54	6.2
Age of the HH (Years)	Households (%)		
<30	16.2	11.6	14.0
30-50	48.7	50.0	49.3
51-60	23.1	16.1	19.7
>60	12.0	19.7	17.0
Mean age (years)	45.9	49.4	47.6
Education of HH	Households (%)		
Illiterate	47.0	75.0	60.7
Read and Write	41.0	15.2	28.4
4-6	6.0	5.4	5.7
7-12	6.0	4.5	5.2

Source: Survey data

In the study area, land holding varies considerably reflecting differences in population density, availability of arable land within the jurisdiction of PA boundaries and frequency of land redistribution. Land holding per household ranged from 0.34 ha to 5.76 ha with a mean of 2.18 ha while the number of plots managed by a household ranged from 1 to 12 with a mean number of 5 plots per household (Table 5.4). The average plot size also varied from 0.31 ha in Debre Birehan to 0.41 in Dendi. During the study year about 40.2% of the sample households leased in some land while 14.4% leased out part of their farmland. Households in Dendi owned significantly larger farm size, fewer and larger sized plots compared to their counterparts in the Debre Birehan district. Also, the number of households who leased in land in Debre Birehan is significantly higher than in Dendi district. The land redistribution in Debre Birehan, which was completed in 1997, has contributed to smaller land holdings and increased land fragmentation as evidenced by the significantly higher number and small sized plots. The land redistribution in Debre Birehan benefited newly formed and women headed households who did not own land for various reasons. However, most of the women headed and newly established young households unable to cultivate by their own due to lack of access to key resources (oxen, labor and seed) leased out their newly acquired land to the former managers (those who lost land). On the other hand, in the Dendi area, land redistribution has not been implemented since the fall of the socialist regime. Consequently, landholdings have remained largely unaffected. Group discussion with farmers in Dendi district, however, revealed that landlessness in the district is rampant, variously estimated between 30% and 40%.

Livestock species that are traditionally raised by farmers in the highlands include cattle, sheep, donkeys, horses and poultry. The average herd size per farm is 4.36, 4.16, and 6.14 cattle, 6.73, 2.6 and 1.64 sheep, in Debre Birehan, upper and mid highlands of Dendi, respectively. Goats are less abundant in the upper highlands. Donkeys are important in Debre Birehan and the mid highlands of Dendi while horses are much more common in the upper highlands of Dendi. About 35%, 36% and 19% of the sample households in Debre Birehan, the upper and mid highlands of Dendi, respectively, do not own the minimum pair of oxen required for land preparation. Households with one or no oxen either lease out their land, acquire additional oxen through social networks known traditionally as *mekenajo*[15] and *debo*[16] or hire the services of oxen in cash or in kind for cultivation.

[15] *mekenajo* is a traditional oxen-pairing system in which a farmer with one ox makes an arrangement with a fellow farmer to pull their oxen and plough in turns.

Table 5.3. Farmer perception of plot characteristics, Central highlands of Ethiopia, 2003

Item	Debre Birehan (Upper highlands) (N=971)	Dendi		All locations (N=1599)
		Upper highlands (N=276)	Mid-highlands (N=352)	
Slop				
Flat	47.0	44.6	75.0	52.9
Medium	47.0	43.5	23.6	41.2
Steep	5.4	12.0	1.4	5.6
Very Steep	0.7	0.0	0.0	0.4
Soil fertility				
Poor	22.5	15.9	9.4	18.4
Medium	50.3	37.7	61.4	50.5
Fertile	25.8	23.6	19.3	24.0
Kossi	1.4	22.8	9.9	7.0
Soil depth				
< 30cm	28.7	36.2	14.8	23.9
30-60 cm	43.4	51.1	70.0	51.0
> 60cm	27.9	12.7	14.2	25.1
Productivity potential				
Poor	28.7	33.0	13.4	26.1
Medium	43.4	54.3	74.7	52.2
Good	27.9	12.7	11.9	21.8
Degradation severity				
Very sever	9.4	29.0	6.3	12.1
Sever	17.3	20.6	20.7	18.4
Light	32.6	18.1	25.9	28.6
None	40.7	33.3	47.2	40.8

Source: Survey data

[16] *debo* is an arrangement whereby neighbouring farmers or relatives with oxen assist in cultivation, free of charge except for the refreshments provided during cultivation.

Table 5.4. Land holdings of sample farmers in Dendi and Debre Birehan Zuria districts, Central highlands of Ethiopia, 2003.

	District		
	Debre Birehan	Dendi	Whole sample
Farm size groups (ha)	Households owning (%)		
<0.5	1.7	0.9	1.3
0.5-1.0	20.5	4.5	12.7
1.01-2.0	47.0	28.6	38.0
2.01-3.0	22.2	25.9	24.0
>3.01	8.5	40.2	24.0
Mean farm size	2.16	3.00	2.18
Plots (parcels) managed	Households managing (%)		
1-3	15.4	42.0	28.4
4-6	41.9	54.4	48.0
>6	42.7	3.6	23.6
Mean number of plots	6.3	3.9	5.1
Plot size (ha)			
Min	0.01	0.02	0.01
Max	1.25	2.70	2.70
Mean	0.24	0.48	0.34

Source: own computations from survey data

5.4.3 Farming systems and crops grown

Two distinct farming systems are identified in the study area based on variations in altitude, rainfall, soil type, topographic conditions and type of associated vegetative cover.

- The barley based mixed crop-livestock production systems of the upper highlands in Debre Birehan and Dendi districts situated above 2,600 meters; and

- The teff-wheat based mixed crop-livestock production system of the mid highlands in Denidi district lying between 2000 and 2600 meters.

In the upper highlands, households have limited crop choice. Barley and wheat are the most preferred and productive crops while faba bean, potato, linseed and lentil are minor crops (Table 5.5). Main season barley (barley grown during the main rainy season) appears to dominate where the cropland is well drained whereas plots with poor internal drainage due to either the accumulation of surface run off (flooding) or poor infiltration of the soil are either used as grazing fields, grow natural pasture for hay making, planted to crops that could do well on residual moisture towards the end of the main season or planted to barley during the short rainy (belg) season. Wheat is grown on selected topo-locations where frost incidence is low and soil fertility is presumed to be high. In the upper highlands of Dandi, a perennial crop known locally as enset (false banana) grown as a backyard crop has become an important food security crop.

Major crop production problems in the barley based farming systems of the upper highlands identified by smallholder farmers in their order of importance include: late on-set of the main season rain mainly affecting long season barley production, soil erosion, frost, low soil fertility, water logging on bottom lands, hail and lack of well adapted legume crops that could be used as rotation crops. Shortage of fuel wood and lack of alternative cash sources particularly in Debre Birehan district has prompted smallholder farmers to divert a significant portion of the animal dung to meet either domestic fuel needs or sold at the local markets to earn cash.

The mid highlands of Dendi district lying between 2,000 to 2,600 meters is mainly characterized by flat to undulating topography. Much of the low lying land (meda plots) suffer from poor infiltrations and water logging due to inadequate surface slope to drain the surface run off. In this sub-study area, unlike the case of the upper highlands where

Table 5.5. Major crops cultivated, mean crop area (ha) and farmers growing (%) in Dendi and Debre Birehan Zuria districts, Central highlands of Ethiopia, 2003.

Crop	Debre Birehan (Upper highlands)		Dendi			
			Upper highlands		Mid-highlands	
	Plots cultivated (%)	Mean area (ha)	Plots cultivated (%)	Mean area (ha)	Plots cultivated (%)	Mean area (ha)
Cereals						
Barley	24.3	0.27	26.7	0.71	1.1	0.24
Wheat	21.6	0.23	9.3	0.65	10.2	0.39
Tef	0.1	0.06	0.0	0.0	32.4	0.65
Maize	0.1	0.25	0.0	0.0	14.1	0.23
Sorghum	0.0	0.0	0.0	0.0	3.3	0.23
Legumes						
Faba bean	18.4	0.25	1.3	0.54	5.0	0.35
Field pea	9.2	0.22	0.3	0.45	0.0	0.0
Lentil	1.7	0.21	0.0	0.0	0.0	0.0
Chick pea	0.0	0.0	0.0	0.0	8.3	0.45
Grass pea	0.0	0.0	0.0	0.0	6.6	0.34
Oil seeds						
Lin seed	1.5	0.13	0.0	0.0	0.0	0.0
Niger seed	0.0	0.0	0.0	0.0	2.2	0.35
Horticulture						
Potato	0.2	0.13	18.0	0.32	0.3	0.17
Enset	0.0	0.0	10.3	0.13	2.2	0.08
Natural pasture	13.5	0.20	4.3	0.48	11.1	0.37
Annual fallow	5.4	0.28	21.3	0.70	0.0	0.0

Source: Survey data

crop choice is limited, a wide variety of crops are grown. Tef, wheat, highland pulses (chick pea, rough pea and faba bean), highland sorghum locally known as *zengada,* and niger seed are grown successfully (Table 5.5). Crop management in the mid highlands of Dendi is largely a function of soil type, soil fertility and slope of the plot in question. The dominant crop management strategies in this farming system include:

- Planting crops such as tef that have got marked tolerance to water logging on relatively fertile land using moderate levels of inorganic fertilizer during the periods of highest rainfall (July-August).
- Planting traditional varieties of durum wheat, chickpea and rough pea most often with out fertilizer late in the season on residual moisture.

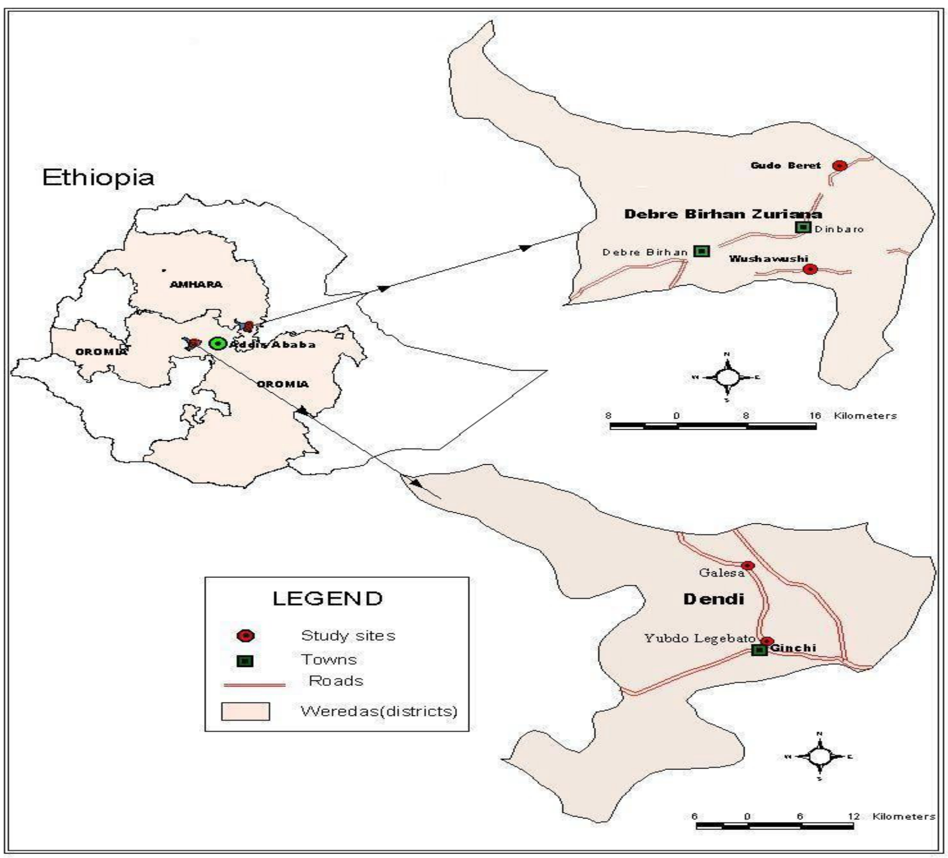

Figure 5.3. Map of the study area.

CHAPTER VI: EMPIRICAL SPECIFICATION AND RESULTS OF THE SOIL DEGRADATION OPTIMAL CONTROL MODEL

This chapter is concerned with the empirical application of the optimal control soil degradation model developed in chapter four. Section one empirically specifies the optimal control model while section two derives the optimal solutions. Section three describes the data and information used to estimate model parameters. Model results are presented and discussed in section four. This section also discusses results of the sensitivity analysis. The last section, section five, concludes by summarizing the results and policy implications of the findings.

6.1 Empirical specification of the control model

The components of the control model developed in chapter four that require empirical specification include the production function (f), the erosion damage function (H), the nutrient decay and regeneration function (N), prices and production costs. Empirical specification and brief description of the control model is provided in the following subsections.

6.1.1 The production function

The arguments in our production function not withstanding factors assumed to be fixed across households (e.g., rainfall) include labor for production (L_Y), capital in the form of tillage inputs (K_Y), top soil depth (SD) and soil nutrients in the form of soil nitrogen (N). Among the functional forms widely used in empirical studies of production relationships are the Cobb-Douglas (C-D) and translog. The C-D functional form is often preferred in empirical studies due to its convenience in estimation and interpretation of parameter estimates. Therefore, for our purpose, a C-D functional form relating crop yield to labor, tillage, nitrogen and soil depth is adopted.

$$f(L_Y, K_Y, N, SD) = Y = AL_Y^b K_Y^c SD^d N^g \tag{6.1}$$

Where Y is annual yield in tons/ha; A is a scale parameter; L_Y is labor inputs for production in person-days/ha; K_Y is capital for production (oxen hours for plowing); SD is topsoil depth in cm; N is nitrogen in tons per ha in the top 10 cm soil depth while b, c, d and g are the technology parameters.

6.1.2 The soil decay (erosion damage) function

Soil decay or erosion damage is a function of soil characteristics such as natural susceptibility of soil to erosion (soil erodibility), plot slope, rainfall intensity (erosivity of rainfall), land cover and land management factors such as presence or absence of soil conservation structures. As has been pointed out in chapter four, households in the highlands could manipulate the rate of erosion either by constructing physical soil conservation structures (conservation effort) and/or intensifying production thus altering the crop cover factor. In this study, the soil decay function is specified as an exponential function relating soil loss to conservation effort (labor inputs for conservation) as follows (subscript i denoting plot category suppressed for simplicity):

$$E(L_S) = \gamma e^{-\alpha L_S} \tag{6.2}$$

Where E (L_S) is the soil loss in tons/ha with conservation effort L_S in person-days/ha, γ is a calibrating parameter representing the average rate of soil loss on the i^{th} plot in the absence of soil conservation structures (depends on rainfall, slope, crop cover and other plot specific characteristics); and α is a positive constant denoting the elasticity of conservation effort. Equation (6.2) implies the higher the conservation effort in the form of labor expended for the construction of physical structures, the lower the soil loss. Conservation effort therefore reduces soil decay.

The second component of the soil damage function relates canopy (crop cover) to soil decay. Brekke et al. (1999) indicated that soil erosion decreases with crop cover (increased production). Building on the specifications of Brekke et al (1999) and Nakhuwma (2004) the relationship of canopy to soil damage is specified as

$$J = \phi(1 - e^{-\nu Y}) \tag{6.3}$$

Where ϕ is a calibrating parameter denoting soil loss on the i[th] plot of known crop cover in the presence of soil conservation structures; ν is the elasticity of canopy and Y is canopy (output). Accordingly the soil decay function (h) is specified as:

$$h = E - J = \gamma e^{-\alpha L_S} - \phi(1 - e^{-\nu Y}) \tag{6.4}$$

The third component of the soil regeneration and decay function is the natural soil regeneration function, Z, assumed constant. Pulling the components together, the aggregate soil regeneration and damage function, therefore, is specified as an additive function:

$$H = Z - h = Z - (E - J) = Z - \tau e^{-\alpha L_S} + \phi(1 - e^{-\nu Y}) \tag{6.5}$$

Where H is the net soil loss in tons/ha while other variables are as described above.

6.1.3 The nutrient regeneration and depletion function

The nutrient regeneration and depletion function (N) has three components: the nutrient augmentation function, G(F), nutrient depletion due to crop harvest, D(Y), nutrient regeneration and decay due to natural processes and soil erosion, $M(Z,L_K,Y)$. Empirical specification of the components of the nutrient regeneration and depletion function is discussed below.

Smallholder farmers in the highlands of Ethiopia use several soil fertility management practices including inorganic fertilizers, farmyard manure as well as fallow and legume rotations. For tractability purposes and following Nakhumwa (2004), the nutrient augmentation function is specified as an aggregate linear function depicted as:

$$G(F) = \beta_1 F \tag{6.6}$$

Where F is the amount of nutrient inputs in kg/ha and β_1 is a parameter that links nutrient inputs to soil nutrients. Similarly, the second component of the aggregate nutrient regeneration and decay function, the nutrient depletion function due to crop harvest (grain and crop residues), is specified as a liner function of the amount of grain and other biomass leaving the plot. Accordingly, the depletion function, D(Y), is given by:

$$D(Y) = \beta_2 Y \tag{6.7}$$

Where Y is total biomass (grain and crop residues) harvested in tons/ha while β_2 is a parameter representing the proportion of nutrients per unit of harvested grain and residue.

The last two component of the nutrient regeneration and depletion function that require empirical specification are the nutrient regeneration and depletion function due to natural soil processes and the nutrient depletion due to soil erosion. In this study, these processes are linked with the soil depth depletion equation specified in equation (6.5). Accordingly, the nutrient damage function due to natural processes and soil erosion damage is specified as follows:

$$M(Z, L_K, Y) = \beta_3\left[Z - \gamma e^{-\alpha L_K} + \phi\left(1 - e^{-\nu Y}\right)\right] \tag{6.8}$$

Where β_3 is a coefficient that converts soil depth reductions into nutrient loss per unit of eroded soil. Given equations (6.6-6.8), the aggregate soil nutrient regeneration and depletion function is specified as follows.

$$N(F, Z, L_K, Y) = \beta_1 F - \beta_2 Y + \beta_3\left[Z - \gamma e^{-\alpha L_K} + \phi\left(1 - e^{-\nu Y}\right)\right] \tag{6.9}$$

6.2 The empirical control model and optimal solutions

As is noted in chapter four, smallholder farmers in the highlands of Ethiopia manage several small plots of land of various soil quality dispersed across microenvironments. Consequently, the soil degradation problem facing smallholder subsistence farmers are grouped into two: reversible soil degradation (nutrient mining) largely arising from net nutrient extraction through crop harvest exceeding replenishment levels and the combined effect of soil nutrient mining and water induced irreversible physical degradation. While nutrient mining is most prominent on low-lying, supposedly deep and fertile plots that are subjected to continuous cropping both nutrient mining and physical degradation are prevalent on uplands that are susceptible to intense erosion by virtue of its slope. Accordingly, two versions of the analytical model presented in chapter four are empirically specified for the two soil degradation scenarios facing smallholder farmers in the highlands of Ethiopia.

6.2.1 The nutrient mining empirical control model and optimal solutions

As noted earlier soil nutrient mining is the most important problem on bottomlands (low-lying). Assuming, irreversible soil degradation is negligible on this category of plots and substituting the specified functions discussed above in the analytical control model developed in chapter four, the empirical nutrient mining control model (time subscripts suppressed) is given by:

$$\text{Max } \Pi_{F,L_Y,K_Y,L_S} = \int_0^{\infty} e^{-\delta t}\left[PAL_Y^b K_Y^c N^g - \left(W_F F + W_L L_Y + W_L L_S + W_K K\right)\right]dt \tag{6.10}$$

Subject to the equation of motion and initial condition:

$$N_0 = \overline{N} \tag{6.11}$$

$$\dot{N} = \beta_1 F - \beta_2 Y + \beta_3\left[Z - \gamma e^{-\alpha L_S} + \phi\left(1 - e^{-vY}\right)\right] \tag{6.12}$$

Where δ is the discount rate; P is the output price; W_F, W_L, W_S, and W_K are prices of fertilizer, labor for production and conservation and capital (tillage), respectively; and $\overline{N}$ the initial soil nitrogen. Accordingly, the Hamiltonian (dynamic profit function) for the nutrient mining scenario would be:

$$\Pi(F, L_Y, L_S, K_Y, \mathrm{N}, \mu) = e^{-\delta t}\left[PAL_Y^b K_Y^c N^g - \left(W_F F + W_L L_Y + W_S L_S + W_K K_Y\right)\right]$$
$$+ \mu\left\{\beta_1 F - \beta_2 Y + \beta_3\left[Z - \gamma e^{-\alpha L_S} + \phi\left(1 - e^{-vY}\right)\right]\right\} \tag{6.13}$$

Consequently, the first order conditions for optimal fertilizer, labor and capital use are (see appendix I, II and III for detailed derivation):

$$\frac{\partial \Pi}{\partial F} = 0 = -e^{-\delta t} W_F + \mu\beta_1 \tag{6.14}$$

$$\frac{\partial \Pi}{\partial L_Y} = 0 = e^{-\delta t}\left(\frac{PbY}{L_Y} - W_L\right) + \mu\frac{bY}{L_Y}\xi \tag{6.15}$$

$$\frac{\partial \Pi}{\partial K_Y} = 0 = e^{-\delta t}\left(\frac{PcY}{K_Y} - W_K\right) + \mu\frac{bY}{K_Y}\xi \tag{6.16}$$

$$\frac{\partial \Pi}{\partial L_S} = 0 = -e^{-\delta t} W_S + \mu\beta_3\tau\alpha\gamma e^{-\alpha L_S} \tag{6.17}$$

$$\dot{\mu} = -\frac{\partial \Pi}{\partial N} = -e^{-\delta t} P\frac{gY}{N} + \mu\frac{gY\xi}{N} \tag{6.18}$$

$$\frac{\partial \Pi}{\partial \mu} = \dot{N} = \beta_1 F - \beta_2 Y + \beta_3\left[Z - \tau e^{-\alpha L_S} + \phi\left(1 - e^{-vY}\right)\right] \tag{6.19}$$

The first order conditions given in equations (6.14-6.19) form a system of six equations in six unknowns. The system is solved for steady state optimal values as explained below.

6.2.1.1 Steady state optimal solutions for the nutrient mining scenario

In a steady state the rate of change of the resource stock and its implicit price are necessarily zero ($\dot{N} = \dot{\mu} = 0$) providing a constant but positive royalty. The reduced form steady state optimal solutions of the four choice variables and the resource stock denoted by L_Y^*, K_Y^*, L_S^*, F^* and N^* for optimal values of labor and capital for production, labor for conservation, fertilizer, and the optimal nutrient stock, respectively, are derived in appendix III and given below.

$$L_Y^* = A^{\frac{1}{\varpi}} \left(\frac{c}{W_K}\right)^{\frac{c}{\varpi}} \left(\frac{b}{W_L}\right)^{\frac{\varpi(c-1)-bg}{\varpi(b+c-1)}} \left(\frac{W_F \delta}{g}\right)^{\frac{-g}{\varpi}} (P - W_F \xi)^{\frac{1}{\varpi}} \tag{6.20}$$

$$K_Y^* = A^{\frac{1}{\omega}} \left(\frac{c}{W_K}\right)^{\frac{\varpi(b-1)-cg}{\varpi(b+c-1)}} \left(\frac{b}{W_L}\right)^{\frac{b}{\varpi}} \left(\frac{W_F \delta}{g}\right)^{\frac{-g}{\varpi}} (P - W_F \xi)^{\frac{1}{\varpi}} \tag{6.21}$$

$$L_s^* = \left(\frac{1}{\alpha}\right) \ln\left(\frac{W_F \beta_3 \tau \alpha}{W_S}\right) \tag{6.22}$$

$$N^* = A^{\frac{1}{\varpi}} \left(\frac{c}{W_K}\right)^{\frac{c}{\varpi}} \left(\frac{b}{W_L}\right)^{\frac{b}{\varpi}} \left(\frac{W_F \delta}{g}\right)^{\frac{b+c-1}{\varpi}} (P - W_F \xi)^{\frac{1}{\varpi}} \tag{6.23}$$

$$F^* = \left\{\beta_2 Y^* - \beta_3 \left[Z - \tau e^{-\alpha L_S^*} + \phi(1 - e^{-vY})\right]\right\} / \beta_1 \tag{6.24}$$

Where : L_S^* is as given by equation (6.22) and Y^* is the optimal output given by

$$Y^* = A L_Y^{*b} K_Y^{*c} N^{*g} \tag{6.25}$$

Where : L_Y^*, K_Y^*, N^* are given by equations (6.20, 6.21 and 6.23), respectively.

6.2.2 The nutrient mining and physical degradation empirical control model and optimal solutions

It has been noted that the soil degradation problem facing smallholder farmers on upland plots is further complicated by intense water erosion, which besides washing away essential soil nutrients along with eroded soil, destroys soil structure, organic matter and topsoil depth resulting in irreversible damage to soil quality. The control model for this scenario thus involves two state equations of motion depicting the evolution of the nutrient stock (N) and soil depth (SD) over time. Substituting the specified functions given in section one into the control model developed in chapter four, the empirical model for the case where nutrient mining and physical soil degradation co-exist (here after referred to as scenario II) is given by:

$$\text{Max } \Pi_{F,L_Y,K_Y,L_S} = \int_0^{\infty} e^{-\delta t}\left[PAL_Y^b K_Y^c N^g SD^d - \left(W_F F + W_L L_Y + W_L L_S + W_K K\right)\right]dt \qquad (6.26)$$

Subject to the equations of motion and initial conditions:

$$SD_0 = \overline{SD} \qquad (6.27)$$

$$N_0 = \overline{N} \qquad (6.28)$$

$$\dot{SD} = Z - \gamma e^{-\alpha L_S} + \phi\left(1 - e^{-vY}\right) \qquad (6.29)$$

$$\dot{N} = \beta_1 F - \beta_2 Y + \beta_3\left[Z - \gamma e^{-\alpha L_S} + \phi\left(1 - e^{-vY}\right)\right] \qquad (6.30)$$

where $\overline{SD}$ is the initial soil depth in cm while other variables are as defined earlier. Accordingly, the Hamiltonian or the dynamic profit function is:

$$\begin{aligned}\Pi(F, L_Y, L_S, K_Y, \mathrm{N}, \mu) = {} & e^{-\delta t}\left[PAL_Y^b K_Y^c N^g SD^d - \left(W_F F + W_L L_Y + W_S L_S + W_K K_Y\right)\right] \\ & + \lambda\left[Z - \gamma e^{\alpha L_S} + \phi(1 - e^{vY})\right] + \mu\left\{\beta_1 F - \beta_2 Y - \beta_3\left[Z - \gamma e^{-\alpha L_S} + \phi\left(1 - e^{-vY}\right)\right]\right\}\end{aligned} \qquad (6.31)$$

The first order conditions for optimal fertilizer, labor and capital use are (details are given in Appendix IV)

$$\frac{\partial \Pi}{\partial F} = 0 = -e^{-\delta t} W_F + \mu\beta_1 \qquad (6.32)$$

$$\frac{\partial \Pi}{\partial L_Y} = 0 = e^{-\delta t}\left(\frac{PbY}{L_Y} - W_L\right) + \lambda\frac{bY}{L_Y}\varphi + \mu\frac{bY}{L_Y}\xi \qquad (6.33)$$

$$\frac{\partial \Pi}{\partial K_Y} = 0 = e^{-\delta t}\left(\frac{PcY}{K_Y} - W_K\right) + \lambda\frac{bY}{K_Y}\varphi + \mu\left(\frac{bY}{K_Y}\xi\right) \qquad (6.34)$$

$$\frac{\partial \Pi}{\partial L_S} = 0 = -e^{-\delta t} W_{L_S} + \lambda \tau \alpha e^{-\alpha L_S} + \beta_3 \tau \alpha \gamma e^{-\alpha L_S} \tag{6.35}$$

$$\dot{\lambda} = \frac{\partial \Pi}{\partial SD} = -e^{-\delta t} P \frac{dY}{SD} - \lambda \frac{dY}{SD} \varphi + \mu \frac{dY}{SD} \xi \tag{6.36}$$

$$\dot{\mu} = \frac{\partial \Pi}{\partial N} = -e^{-\delta t} P \frac{gY}{N} - \lambda \frac{gY}{N} \varphi + \mu \frac{gY}{N} \xi \tag{6.37}$$

$$\frac{\partial \Pi}{\partial \lambda} = \dot{SD} = Z - \tau e^{-\alpha L_S} + \phi\left(1 - e^{-vY}\right) \tag{6.38}$$

$$\frac{\partial \Pi}{\partial \mu} = \dot{N} = \beta_1 F - \beta_2 Y + \beta_3 \left[Z - \tau e^{-\alpha L_S} + \phi\left(1 - e^{-vY}\right)\right] \tag{6.39}$$

The first order conditions given in equations (6.32-6.39) form a system of eight equations in eight unknowns. The system is solved for steady state optimal values as explained below.

6.2.2.1 Steady state optimal solutions for the nutrient mining and physical soil degradation scenario

As in scenario I, in a steady state the rate of change of the resource stock and its implicit price are necessarily zero ($\dot{SD} = \dot{N} = \dot{\lambda} = \dot{\mu} = 0$) providing a constant but positive royalty. The reduced form steady state optimal solutions of the four choice variables and the resource stock denoted by $\mathrm{L}_\mathrm{Y}^*, \mathrm{K}_\mathrm{Y}^*, \mathrm{L}_\mathrm{S}^*, \mathrm{F}^*, \mathrm{N}^*$ and SD^* for optimal values of labor and capital for production, labor for conservation, fertilizer, and the optimal resource stocks (nitrogen and soil depth), respectively, are derived in appendix IV and given below.

$$L_Y^* = A^{\frac{-1}{\theta}} \left(\frac{W_F \delta}{g}\right)^{\frac{g}{\theta}} \left(\frac{b}{W_L}\right)^{\frac{g+d+c-1}{\theta}} \left(\frac{c}{W_K}\right)^{\frac{-c}{\theta}} \left(\frac{\varphi d}{\delta \zeta}\right)^{\frac{-d}{\theta}} \left(\frac{1}{\zeta + P - W_F \xi}\right)^{\frac{1}{\theta}} \tag{6.40}$$

$$K_Y^* = A^{\frac{-1}{\theta}}\left(\frac{W_F\delta}{g}\right)^{\frac{g}{\theta}}\left(\frac{b}{W_L}\right)^{\frac{-b}{\theta}}\left(\frac{c}{W_K}\right)^{\frac{g+d+b-1}{\theta}}\left(\frac{\varphi d}{\delta\zeta}\right)^{\frac{-d}{\theta}}\left(\frac{1}{\zeta+P-W_F\xi}\right)^{\frac{1}{\theta}} \tag{6.41}$$

$$N^* = A^{\frac{-1}{\theta}}\left(\frac{W_F\delta}{g}\right)^{-\left(\frac{d+c+b-1}{\theta}\right)}\left(\frac{b}{W_L}\right)^{\frac{-b}{\theta}}\left(\frac{c}{W_K}\right)^{\frac{-c}{\theta}}\left(\frac{\varphi d}{\delta\zeta}\right)^{\frac{-d}{\theta}}\left(\frac{1}{\zeta+P-W_F\xi}\right)^{\frac{1}{\theta}} \tag{6.42}$$

$$SD^* = A^{\frac{-1}{\theta}}\left(\frac{W_F\delta}{g}\right)^{\frac{g}{\theta}}\left(\frac{b}{W_L}\right)^{\frac{-b}{\theta}}\left(\frac{c}{W_K}\right)^{\frac{-c}{\theta}}\left(\frac{\varphi d}{\delta\zeta}\right)^{\frac{g+c+b-1}{\theta}}\left(\frac{1}{\zeta+P-W_F\xi}\right)^{\frac{1}{\theta}} \tag{6.43}$$

$$L_S^* = \frac{1}{\alpha}\ln\left[\frac{\gamma\alpha}{W_{L_S}}\left(\frac{\varphi}{\zeta}+\beta_3\right)\right] \tag{6.44}$$

$$Z^* = \gamma e^{-\alpha L_S^*} - \phi\left(1-e^{-\nu Y^*}\right) \tag{6.45}$$

$$F^* = \left\{\beta_2 Y^* - \beta_3\left[Z - \tau e^{-\alpha L_S^*} + \phi(1-e^{-\nu Y})\right]\right\}/\beta_1 \tag{6.46}$$

Where : L_S^* is as given by equation (6.44) and Y^* is the optimal output given by

$$Y^* = AL_Y^{*b}K_Y^{*c}N^{*g}SD^{*d} \tag{6.47}$$

Where : L_Y^*, K_Y^*, N^*, SD^* are given by equations (6.40, 6.41, 6.42 and 6.43), respectively.

6.3 Estimating the control model parameters

This section discusses the data and information used to estimate parameters of the empirical control model presented in section one of this chapter. In an ideal situation all relevant economic and environmental data required for numerical analysis need to be obtained from a single unified source of a common reference year. For this study, however, no such data existed. The study, therefore, draws heavily on several primary and secondary sources for estimating parameter values and subsequently solving the two versions of the control model.

The control model discussed above and empirically specified and solved in subsequent sections assumes smallholder farmers cultivate a single crop (teff). Furthermore, cultivated area is assumed to be fixed and the decision whether to reduce or expand the cultivated area is assumed to be exogenous. In reality, however, crop rotations are the norm than the exception and hence crop choice itself could be considered as a soil conservation practice in addition to conventional inputs[17]. In this model, crop mix, as a choice variable is not considered due to data limitations.

6.3.1 Production technology parameters

The arguments[18] of the yield function in the nutrient mining scenario (scenario I) are labor (L_Y), capital (K_Y) and soil nutrient (N) whereas the arguments in scenario II, besides those in the scenario I include soil depth (SD). The yield-input relationship for scenario I is estimated from a cross-section household survey data collected in the study area for this purpose while the yield-soil depth relationship is inferred from previous studies.

The estimated yield parameters from the application of OLS procedure to the household survey data are given in Table 6.1. The F statistics of the estimated model is highly significant (P=0.000) suggesting the independent variables have good explanatory powers. The R^2, however, is low which is not uncommon for cross-section data. A Breusch-Pagan test for heteroskedasticity failed to reject the null hypothesis of constant variance (Prob > χ^2 = 0.1342) suggesting the application of OLS to the data is justifiable. Detailed discussions on econometric problems associated with the application of OLS to cross-section household data and alternative specifications are provided in chapter 7.

As expected, N is positively and significantly related with grain yield of teff suggesting a one percent increase in N increases yield by 0.3%. Similarly, labor has a positive and

[17] See Goetz (1997) for detailed discussion and modeling of optimal and social inter-temporal path of soil use considering crop choice as a soil conservation practice.
[18] District and agroecology were not included as arguments in the estimation of the technology prameters for the test crop, tef, is restricted to the mid highlands of Dendi (see Table 5.5) for details.

significant impact on teff yield. On the other hand, oxen hours, a proxy for capital although with the expected positive sign, is not statistically significantly related with grain yield of teff. As has been observed in the study area and elsewhere in the highlands traction power is a critical input in teff cultivation while weed control is largely done with herbicides. Plowing frequency, however, showed little variation across household groups for the same crop. Households with inadequate traction power usually either rent in oxen to meet the minimum number of plowings necessary for a reasonable seed bed, switch to crops that require less frequent plowing (legumes, oil seeds) or lease out to households who have adequate traction power. As a result, it might be the timing of operations rather than total number of plowings that likely explain yield variability experienced by households for the same crop. Data on the timing of plowing and weeding, however, proved difficult to collect and hence were not included in the analysis.

The estimated parameters of the yield function reported in table 6.1 have ascertained the yield-soil nutrient relationship. However, the estimated parameters for N appear to be large while that of K_Y is small. Several studies in the highlands of Ethiopia have documented a positive and significant yield impact of commercial fertilizer, labor and capital on grain yield under smallholder farming conditions. Notable among these studies are Tadesse et al. (2000) in Bako area, Western highlands; Hassena et al. (2000) in Asasa district, Southeastern highlands; and Croppenstedt and Demeke (1997) at a national level. The results, however, cannot be directly compared due to the use of different functional forms and measurements for the dependent (value and quantity) and independent (qualitative and quantitative) variables. One study worth mentioning is that of Tadesse et al. (2000) who estimated a C-D production function for smallholder maize production, which showed a positive and significant yield impact of inorganic fertilizers (coefficient of 0.199 and 0.175) and oxen hours (0.144 and 0.201) in maize production for extension project participating and non-participating households. The said parameter estimates will be used to gauge the sensitivity of model results to changes in parameter values.

Table 6.1. Parameter estimates of the Cobb Douglas production function for smallholder teff production in the Central highlands of Ethiopia, 2003

Variable name	Coefficient	T-value	Sig. level
lnN	0.2980	3.900	0.000
$\ln K_Y$	0.1194	0.340	0.735
$\ln L_Y$	0.1492	1.980	0.051
lnConstant[19]	-2.3790	-1.410	0.162
No of observations	70		
R^2	0.2339		
Adjusted R^2	0.1991		
F-value	6.72		0.000

6.3.2 Parameters of the erosion damage function

In the highlands of Ethiopia, except for experimental plots of SCRP sites, erosion rates are not measured but are often estimated to be high reaching over 100 tons/ha. In the absence of reliable soil loss estimates for smallholder agriculture, in this study, soil loss predictions based on the USLE modified for Ethiopia (Hurni, 1985) and applied by Shiferaw and Holden (1999) for the highlands are used (Appendix VI). The estimated soil loss rates for the two plot categories considered (bottom and uplands) representing nil/mild physical soil degradation and sever/moderate physical degradation with and without soil conservation were substituted into equation (6.2) and solved for the elasticity of conservation effort (α) for the respective plot categories. Accordingly, considering the widely used conservation structures, soil bunds on bottom lands and a combination of stone/soil bunds on slopping land and a conservation effort of 56 person-days/ha and 112 person-days/ha required for initial construction of on low-lying and upland plots,

[19] The anti-log value is 0.092648

respectively, the elasticity of conservation effort (α)[20] is calculated to be 0.01911 and 0.00956, for bottom and upland plots, respectively.

The contribution of canopy to reducing soil damage is specified as an exponential function. Brekke et al (1999) indicated that raising maize yields from the current low level to an achievable level of 2.5 ton/ha is likely to reduce erosion rates by 12% to 25%. Accordingly, the elasticity of canopy, ν, in equation (6.3) is set at a conservative rate of 0.12 while the parameter, ϕ, is the predicted soil loss of a typical farm under soil conservation.

The initial topsoil depth for the two types of plots considered, severely degraded and none/slightly degraded plots, based on farmer interviews and previous studies is considered to be 30 cm and 70 cm, respectively.

Various studies reported the natural rate of soil regeneration to vary between 4.5 ton/ha to 12 ton/ha (McConnel, 1983; Goetz, 1997). In the highlands of Ethiopia, while erosion is generally considered rampant, the natural rate of soil regeneration is believed to be low. In this study, the natural rate of soil regeneration (Z) is fixed at a conservative rate of 5 ton/ha. All parameters are presented in Table 6.2.

6.3.3 Parameters of the nutrient decay and regeneration function

As stated earlier, the nutrient augmentation function is assumed to be an aggregate function represented by $\beta_1 F$. Assuming that inorganic N is a perfect substitute to natural soil N and following Nakhumwa (2004), the parameter β_1 is set at one implying a unit

[20] For instance, for low lying plots (bottom lands) with parameter values of $[E(L_s) = \phi = 6.9, \gamma = 16.94, L_s = 56]$ the elasticity of conservation effort (α) could be calculated by substituting these values into the following equation derived from equation (6.2): $\alpha = \frac{1}{L_s}\left(\ln\frac{\gamma}{\phi}\right)$

external source of nutrient contributes exactly the same unit of nutrients to the soil nutrient pool. A sensitivity analysis using an augmentation coefficient of 0.75 is conducted to assess the sensitivity of model results to changes of the augmentation coefficient.

Likewise the parameter for the crop damage function, β_2, is assumed to be constant representing the proportion of nitrogen present in the removed biomass (grain and residue). Various studies in Ethiopia reported N content ranging from 2.09% to 2.20% and 0.74% to 0.80% in the grain and straw of the teff crop, respectively (Kidanu et al., 1999). Using average values, the crop damage parameter (β_2) is set at 29.15 kg/ton of harvested product, respectively.

The parameter β_3 representing soil nitrogen lost along with eroded soil is a constant proportion of soil nitrogen available in the soil. The nitrogen content for two soil quality categories considered in the study was obtained from recent soil analyses conducted by the Holetta Agricultural Research Center (HARC). The total N content of the sampled soil in the mid highlands ranged between 0.20% and 0.48% for bottomlands and between 0.20% and 0.24%, for upland plots. Another soil analysis based on composite soil samples taken from 15 smallholder farmers' fields in the Central highlands conducted as part of a soil fertility management on-farm trial gave a total N content ranging from 0.17% to 0.31% with a mean of 0.22%. Considering a soil bulk density of 1g/cc^3, which translates to 100 tons of soil per cm of soil depth (Shiferaw and Holden, 1999) and an average total nitrogen content of 0.22% for bottomlands and 0.17% for uplands, the total N content would be 220 kg/cm and 170 kg/cm soil depth for bottom and upland plot categories, respectively. Therefore, the coefficient of the nutrient depletion and regeneration function (β_3) is set at 2.2 kg/ton and 1.7 kg/ton for bottom and upland plot categories. Sensitivity analysis using the lowest and highest reported soil N content will also be conducted.

Table 6.2. Summary of model parameters of the soil nutrient and soil depth dynamics of the control model

Parameter description	Variable	Value by plot category	
		Bottom	Uplands
Initial soil depth (cm)	SD_0	70	30
Initial soil N level (%)	N_0	0.22	0.17
Initial N stock in the upper 10 cm (kg)	N(10)	2200	1700
Natural rate of soil regeneration (ton/ha)	Z	5	5
Estimated soil loss with conservation (ton/ha)	ϕ	6.97	18.61
Estimated soil loss without soil conservation (ton/ha)	γ	16.94	54.27
Elasticity of conservation effort	α	0.01911	0.00956
Elasticity of canopy	v	0.12	0.12
Coefficient of nutrient augmentation function	β_1	1	1
Coefficient of depletion function (N kg/ton of grain)	β_2	29.15	29.15
Coefficient of net nutrient depletion and regeneration due to erosion (kg/ton)	β_3	2.2	1.7

6.3.4 Prices and production costs

The price of teff is set at 1825 Birr/ton based on 2001/2 weighted annual average producer prices of white, mixed and red seeded grain collected at Holetta local market, some 45 km west of Addis Ababa. Similarly, the price of nitrogen is calculated from the widely used commercial fertilizer DAP which contains 18/46 N/P_2O_5. Based on the 2001/2 price, which was 141.7 Birr per a 50 kg bag of DAP fertilizer in the Holetta area, the price of a kg of N is calculated to be 15.74 Birr.

In the study area, oxen rental market is highly imperfect due to the skewed distribution of oxen and the seasonality of demand for traction. Nonetheless, farmers reported a rental rate of 15 to 20 Birr per day for the services of a pair of oxen for plowing and have been used to calculate the cost of tillage[21] inputs.

In the highlands of Ethiopia, the farm family is the major labor source for agricultural and soil conservation works. Nonetheless, few households reported having used hired labour for agricultural purposes. Payments to hired labour often involve a combination of cash payment of 5 to 8 Birr/day as well as lunch and refreshments. Taking into account the in kind payments, the wage rate, is thus set at 6 Birr and 10 Birr per day for the slack and peak periods of agricultural activities, respectively. Most soil conservation public projects are implemented during the off-season where there are very little alternative job opportunities. Households who construct or maintain soil conservation structures on own managed plots are often conducted during the off-season using family labor. Hence, the appropriate wage rate to use for labour in conservation would be the off-season rate, which is 6 Birr per day.

Labor requirements for constructing soil conservation structures on croplands are based on SCRP work norms cited in Shiferaw and Holden (2001). Conservation labour requirements depend on the type of structure (soil or stone bunds) as well as the slope of the plot. In general, labour requirements are higher for stone bunds than soil bunds. Also, labour requirement tend to increase, as the plot gets steeper. For our purpose, assuming an average slope of 10% for demarcating bottom plots from uplands, the initial labour requirement for constructing soil bunds is fixed at 56 person-days/ha and 112 person-days/ha on bottom and upland plots, respectively. These figures are used to calculate the elasticity of conservation effort (α) in equation (6.2) (see footnote 19).

In Ethiopia, long-term institutional credit to smallholders is unavailable. Nonetheless, short-term institutional credit for the purchase of inorganic fertilizers and related inputs

[21] Assuming a pair of oxen is used for five hours in a normal working day and a daily wage rate of 10 Birr for the oxen handler (cultivator) the hourly oxen rental rate is calculated to be Ethiopian Birr 5.

are provided at an annual interest rate of 12%. For other needs, most smallholders relay on the informal credit market that charges an exorbitant interest rate reaching 120% per annum (10% per month). Considering the institutional interest rate, the discount rate for the base scenario is set at 9%. A lower discount rate of 6% and higher rate of 12% and 24% are also used to test the sensitivity of model results to changes in the discount rate. It is worth noting that the discount rates used are rather very low compared to the time rate of preference of 54% believed to prevail among smallholder farmers in Ethiopia (Holden et al., 1998).

6.4 Model solutions

This section applies the empirical control model to numerically solve optimal steady state values of the control variables, the resource stock and its implicit price. The optimal desirable steady state solution is then compared with profit maximizing static solutions and current farmer practices to gauge whether or not smallholder farmers consider the dynamic costs of nutrient mining and physical soil degradation into their production decisions. Lastly, sensitivity analyses are conducted to test the robustness of model results to changes of basic assumptions and key model parameters.

6.4.1 Empirical model results of the nutrient mining control model

Optimal values of the choice variables (L_Y, K_Y, L_S and F), output (Y) and the resource stock, N under the dynamic (steady state equilibrium) and static decision rules for the nutrient mining scenario along with average current resource use pattern for smallholder teff production in the Central highlands of Ethiopia are presented in Table 6.3. The dynamic steady state solutions are solved using equations (6.20-6.25) of this chapter whereas the static solutions are based on equations (5.8 - 5.10) given in Appendix V. Model results of the base run are based on the following parameters: a nutrient augmentation coefficient of unity (β_1=1), nutrient extraction by crop ($\beta_2 = 29.15$ kg N per ton of harvested product), net nutrient depletion due to erosion and natural processes ($\beta_3 = 2.2$ kg

N per ton of eroded soil), a discount rate of 9% and other biophysical and economic parameters discussed in section 6.2.

Results of the base run revealed that optimal output and input levels under the dynamic decision rule are much higher than the requirements of the static decision rule (Table 6.3). For instance, steady state optimal output under the dynamic decision rule is 1.53 ton/ha compared to 0.42 ton/ha of the static decision rule. The optimal inorganic N input necessary to achieve and sustain the optimal production level indefinitely under the dynamic decision rule, albeit other things being constant, stands at 55 kg/ha compared to the requirements of the static decision rule, which averages at 14 kg/ha. A comparison of the net benefits also clearly shows the superiority of the dynamic steady state optimal solution over the pure profit maximizing static solutions. Hence, the static decision rule could be considered sub optimal compared to the socially desirable steady state optimal input and output levels.

The result that the dynamic decision rule provides a sustainable use of the soil resources (higher inorganic N inputs, soil conservation effort and lower soil loss rates and hence higher soil quality and consequently higher output level) is because the dynamic decision rule considers the effects of current erosion and N extraction rates on levels of the resource stock and output in subsequent year. The dynamic decision rule, therefore, requires that smallholder farmers increase their investment levels not only on yield increasing non-soil inputs (labor and capital for production) but also raise the level of use of soil inputs (labor for conservation and inorganic N) that have long-term desirable effect on soil quality and soil productivity. On the other hand, the static decision rule concerned with the maximization of short-term benefits ignores the effect of current actions (level of erosion and nutrient application rates) on subsequent years' level of the resource stock and output thus provides insufficient erosion control and N fertilizer application rate. Static optimizers ignoring long-term costs, although, enjoy considerable savings in annual costs pay a higher long-term price in terms of reduced soil quality and hence lower yields.

Comparisons of current average farmer practice with the dynamic and static decision rules suggest that current farmer practice follows neither the dynamic nor static decision rule. Output under current practice is higher than the static solution (0.71 ton/ha against 0.42 ton/ha) but much lower than the steady state optimal level. Furthermore, the level of use of soil and non-soil inputs diverged considerably. Of particular significance is the level of capital input under current production, which averages at 94 oxen hours/ha compared to 18 oxen hours/ha under the static optimization. Moreover, current inorganic N application rate in teff production is well above the requirements of the static decision by about 67% (24.1 kg/ha against 14.4 kg/ha) but much lower than the desirable steady state level of 54.8 kg/ha which entails a net nutrient extraction of 16.2 kg/ha. Consequently, current resource use pattern involves a total user cost[22] of Ethiopian Birr of 255.3 per ha (USD[23] 29.7 per ha). Current soil fertility management and conservation practices are thus far from optimal to offset the soil physical degradation and nutrient mining characterizing the highlands. The above results confirm the widely claimed hypothesis that private optimal path of soil use diverges from the socially optimal path. Among the reasons for the existence of this divergence is the high rate of time preference that smallholder farmers' display in their production and consumption decision-making processes. This issue is more fully considered in sensitivity analysis described below. It is worth noting that the steady state socially desirable optimum inorganic N (55 kg/ha) is close to the agronomic recommended N fertilizer rate of 60 kg/ha currently promoted by the extension package program for the cultivation of small cereals including teff in the highlands of Ethiopia.

Nonetheless, despite the fact that current smallholder teff production practice is sub optimal compared to the desirable steady state dynamic solutions, the fact that current inorganic N application rate is higher by 67% than the static optimal level (24.1 kg/ha against 14.4 kg/ha) suggests that smallholder farmers somehow consider some of the

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[22] Barbier (1992) defined user costs as the loss of future productivity due to erosion caused by current use for crop production. In this study, user costs are the annul loss in soil productivity due to changes in the nutrient stock. Hence, total user costs are calculated by multiplying the dynamic price of N with the net change in the nutrients stock.

[23] 1 USD=8.6 Ethiopian Birr

externalities of nutrient mining. The finding that smallholder farmers current resource use pattern although sub optimal as it is compared to the desirable steady state level do not completely ignore the user costs of nutrient mining agrees with the findings of Nakuhumua (2004) for smallholder maize producers in Malawi.

Table 6.3. A comparative analysis of resource use pattern among dynamic and static decision rules and current farmer practice for the nutrient mining scenario

Item	Variable	Decision rule		Current practice
		Dynamic (steady state)	Static	
1	Labor for production (Person-days/ha)	32	11	20
2	Labor for conservation (Person-days/ha)	28	0	16
3	Capital for production (oxen hours/ha)	51	18	94
4	Inorganic fertilizer (N kg/ha)	54.83	14.38	24.12
5	Output (teff grain ton/ha)	1.53	0.42	0.71
6	Net soil loss (ton/ha) [1]	0.00	11.60.	8.90
7	Net N extraction (kg/ha) [2]	0.00	23.27	16.22
8	Resource stock (N kg/ha)	448.25	N.A.	N.A.
9	Marginal user costs of N (Birr/ha) [3]	15.74	15.74	15.74
10	Total user costs of N (Birr/ha) [4]	0.00	366.32	255.33
11	Net private benefit (Birr/ha) [5]	1189.24	329.33	157.92
12	Net social benefit (Birr/ha) [6]	1189.24	-36.99	-97.41

N.A.= Not applicable
[1]calculated based on equation (6.5);
[2]calculated based on equation (6.9);
[3]calculated based on equation (6.14);
[4]toal user costs of N are calculated by multiplying marginal user costs of N (item 9) by the net N extraction (item 7);
[5]gross benefit minus total costs;
[6]net private benefit (item 11) minus total user costs (item 10).

6.4.2 Sensitivity analysis of the empirical soil nutrient mining model

As noted in section 6.4.1 above, optimal values of the choice variables, output and resource stock are derived based on mean soil and non-soil parameter values. Average values, however, hide valuable information as rates of soil erosion and other soil characteristics are plot and location specific and change considerably over time due to climatic variations, slope, topography, etc. Model results are also sensitive to assumed discount rates and other input and output prices. Sensitivity analysis is thus conducted to assess the robustness of the optimal steady state solutions to changes in parameter values and key assumptions.

The initial soil N stock is the most important variable in the nutrient mining control model and varies considerably across farms and plots managed by the same household. In the base run the initial N content of soil is assumed to be 0.22%. Changing the N content of soil to the lowest observed level (0.17%) and highest (0.34%) and still maintaining the assumption that inorganic fertilizers are perfect substitutes of natural N, appears to have little impact on steady state equilibrium levels of the N stock, output and non-soil inputs (labor and capital for production) (Table 6.4). However, the assumption of above average N content of soil (0.34% N) resulted in increased level of conservation effort (from 28 to 55 person-days/ha, up by 96%) but reduced level of inorganic N input (55 to 48 kg/ha, lower by 13%). On the other hand, the assumption of below average N content of soil (0.17% N) raised the optimal level of inorganic N to 58 kg/ha (up by 6%) but lowered the conservation effort to 12 person-days/ha (lower by 57%) compared to the base run. These results suggest that conservation labour and inorganic N are substitutes and hence the optimal soil fertility management strategy depend on the soil fertility status (actual or perceived) of the plot in question. On plots with above average soil fertility where the marginal reduction in soil quality due to the use of one additional unit of conservation labour is higher than the marginal contribution of inorganic N to soil quality, the optimal soil management strategy would be to increase conservation effort (more conservation labor input) but less inorganic N. On plots with lower than average soil fertility where the marginal reduction of soil quality due to the use of one additional unit of conservation labor is less than the marginal contribution of inorganic N to soil quality, the optimal strategy would be to use less soil conservation but more inorganic N. Therefore, initial N content of soil affects optimal levels of conservation effort and inorganic N inputs but not the optimal steady state N stock level. It should be noted that the above results depend on the strong assumption of perfect substitutability of inorganic N for natural soil N. These results, therefore, suggest that improving smallholder farmers' skills in soil fertility assessment techniques through extension education and other appropriate medium is likely to contribute to a more efficient use of household resources including the soil wealth.

Changing the coefficient of the augmentation function, (β_1), from 1 to 0.75, which in effect implies that inorganic fertilizers are less than perfect substitutes of natural soil N, but still maintaining other parameter values at the base run level would have very little effect on the optimal steady state levels of labour and capital for production, labour for conservation and the level of the nutrient stock. It, however, increased the optimal level of inorganic N fertilizer required for maintaining the optimal output level indefinitely by about 33%. The inorganic N input requirements were increased from 55 kg/ha to 73 kg/ha, from 48kg/ha to 64kg/ha and 58 kg/ha to 77 kg/ha on plots with average, above average and below average N content of soil, respectively, clearly indicating that increased inorganic N levels are needed to compensate for the less than perfect substitutability of inorganic N for natural soil N. The simulation results thus suggest that improved agronomic practices that enhance nutrient use efficiency (e.g. practices that reduce N leaching such as N fertilizer placement techniques and split N fertilizer application) would have a positive contribution to soil quality and hence to a more sustainable use of soil resources.

Sensitivity analysis was also conducted with respect to changes in the output elasticity of N and capital (oxen hours). A 10% improvement in the output elasticity of N fertilizer from 0.2980 to 0.3278, all other parameter values kept at the base run level, would have the effect of raising the optimal levels of non-soil inputs (labour and capital for production), inorganic N, output and the resource stock by more than 50%. On the other hand a 10% decrease in the output elasticity of N would lower the levels of non-soil inputs, inorganic N, output and the resource stock. Similarly a rise/fall in the output elasticity of capital would have a similar effect as in the elasticity of output with respect to inorganic N fertilizer. The simulation results, therefore, suggest that technical innovations such as improved agronomic practices and improved crop varieties that improve nutrient use efficiency would play a key role in raising productivity and build up the soil nutrient stock.

Steady state optimal values are found to be highly sensitive to the assumed discount rate. For instance raising the discount rate from 9% (base run) to 12% and further to 24%, all other parameter values kept at the base run level, reduced the optimal levels of non-soil inputs, the resource stock and output considerably but raised the net rate of soil loss suggesting households over exploit the resource stock as the resource is considered worth more now than in the future. It is worth noting that the optimal steady state production labour and inorganic N input and output levels tend to converge to current average practice levels as the discount rate increases beyond 24% suggesting smallholder farmers discount the future heavily. Lowering the discount rate say from 9% (base run) to 6% would have the opposite effect: raised the optimal steady state levels of labour and capital use for production, inorganic N fertilizer, the resource stock and output with a concomitant fall in the rate of soil loss. The above simulation results agree with the widely held view that smallholder farmers discount the future heavily (display a high rate of time preference) and that private optimal path of soil use diverge considerably from the desirable steady state (socially optimal) path (Burt, 1983; Lafrance, 1992; Clarke, 1992; Bishop, 1995; Holden et al., 1998). In many developing countries including Ethiopia the high rate of time preference displayed by smallholder farmers is believed to be associated with poverty, risk aversion behavior and land tenure insecurity. Therefore, measures that reduce smallholder farmers rate of time preference such as improved land tenure security, access to credit and actions targeted at reducing poverty would raise the future worth of soil resources thus provide incentives for the adoption of SWC measures which in turn contribute to a more sustainable use of soil resources.

In most developing countries input and output pricing policies has remained the most important policy tools employed to attain various development objectives deemed desirable by government. It is therefore important to assess the effect of input and output price changes on steady state optimal values. Simulation results of a 25% increase in the price of inorganic N lowered the optimal input levels of labor and capital for production, inorganic N, the resource stock and output. It, however, induced a rise in conservation effort and hence reduced the net soil loss. On the other hand, a similar percentage fall in the price of fertilizer had the opposite effect. While production labour, capital and fertilizer and output increased, the level of conservation effort reduced, which consequently raised the net rate of soil loss. It should be noted that, although, the level of conservation effort is lower than before the fall in price, the optimal nutrient stock increased. This might be due to the fact that the increase in the level of fertilizer use triggered by the fall in fertilizer price more than compensated the nutrient lost along with eroded soil. This negative relationship of an increase/decrease in fertilizer price and a rise/fall in conservation effort could be explained by the relative price changes of fertilizer and conservation labour which induced substitution effect. As the price of fertilizer increases the opportunity cost or shadow price of the nutrient stock rises relative to the price of conservation labour providing the resource manager incentives to substitute conservation effort for inorganic N. On the other hand, a fall in the price of fertilizer lowers the shadow price of the nutrient stock, which consequently raises the relative price of conservation effort thereby reduce the managers incentive for conservation.

The effect of output price rise/fall has a similar effect to a fall/rise in the price of fertilizer with one exception. While a rise/fall in the price of fertilizer would have the effect of increasing/reducing conservation effect, in this study, change in the price of output did not impact the level of conservation effort. The above results agree with the findings of Clarke (1992) who reported that the effect of output price change among other things depend on the existence of viable conservation technologies as well as the complementarity/substitutability of inputs and hence effects of output price change may go either way. Therefore, policies targeted at improving market access (improvement in road networks), improving the efficiency of existing input and output markets (reduce transaction costs) that ensure the delivery of inorganic fertilizers at the right time, product mix and reasonable price is likely to raise the use of inorganic fertilizers which ultimately contributes to a more sustainable use of soil resources.

Table 6.4. Sensitivity analysis with respect to changes in the biophysical parameters of soil N content, coefficients of the augmentation function and elasticity of output with respect to N fertilizer for the nutrient mining scenario

Variable	Base run Soil N (0.22%) β_1=1 β_2=29.15 β_3=2.2	Soil N (0.17%)	Soil N (0.34%)	Nutrient augmentation coefficient (β_1=0.75)			Output elasticity of N (b)	
		β_1=1 β_2=29.15 β_3=1.7	β_1=1 β_2=29.15 β_3=3.4	Soil =0.22% β_2=29.15 β_3=2.2	Soil =0.17% β_2=29.15 β_3=1.7	Soil =0.34% β_2=29.15 β_3=3.4	10% increase β_1=1 β_2=29.15 β_3=2.2	10% decrease β_1=1 β_2=29.15 β_3=2.2
Labor for production [1]	32	31	33	32	31	33	54	20
Labor for conservation[1]	28	12	55	28	12	55	28	28
Capital for production[2]	51	50	52	51	50	52	87	32
Inorganic fertilizer (kg/ha)	55	58	48	73	77	64	84	39
Yield of teff (ton/ha)	1.53	1.52	1.55	1.53	1.52	1.55	2.60	0.97
Net soil loss (ton/ha)	4.65	7.83	0.82	4.65	7.83	0.82	3.96	5.04
MUC[3] (Birr/kg of N)	15.74	15.74	15.74	20.99	20.99	20.99	15.74	15.74
Resource stock (N kg/ha)	448	444	459	448	444	459	836	256
Net benefit (Birr/ha)	1189	1231	1158	902	928	906	2269	622

Note: [1]person-days/ha, [2]oxen hours/ha, [3]marginal user cost

Table 6.5. Sensitivity analysis with respect to changes in the discount rate, inorganic fertilizer and output price for the nutrient mining scenario

Variable	Base run	Change in discount rate (δ)			Change in price of N fertilizer (W_F)		Change in output price (P_Y)		25% rise in P_Y and	25% fall in W_F and
	δ=9%	δ=6%	δ=12%	δ=24%	25% rise	25% fall	25% rise	25% fall	δ=24%	δ=24%
Labor for production[1]	32	42	26	16	23	46	61	13	31	23
Labor for conservation[1]	28	28	28	28	42	10	28	28	28	10
Capital for production[2]	51	67	42	26	36	74	98	20	50	38
Inorganic fertilizer (N kg/ha)	55	68	47	34	40	77	74	38	44	49
Yield of teff (ton/ha)	1.53	2.02	1.26	0.78	1.18	2.06	2.22	0.91	1.13	1.05
Soil loss (ton/ha)	4.65	4.32	4.84	5.19	2.73	7.90	4.19	5.09	4.93	8.59
Resource stock (N kg/ha)	448	889	276	86	255	866	862	179	165	165
Net benefit (Birr/ha)	1189	1689	910	426	701	1951	2625	255	1158	846

Note: [1]person-days/ha, [2]oxen hours/ha, other parameters are set at the baseline scenario level: soil N of 0.22%, $\beta_1 = 1$, $\beta_2 = 29.15$ and $\beta_3 = 2.2$

6.4.3 Empirical model results of the nutrient mining and soil physical degradation control model (scenario II)

This section applies the empirical control model to the soil degradation problem smallholder farmers face on sloping lands where both nutrient mining and soil physical degradation co-exist. Output in this scenario is not only a function of labor, capital (oxen hours) and the nutrient stock (N) but also topsoil depth (SD). Parameter values of the yield function, thus, need to be re-estimated with the inclusion of SD. Unfortunately, available data did not allow us to estimate the impact of SD on crop output. Rather, the output elasticity of SD is inferred from previous studies. Shiferaw and Holden (1999) in the Central highlands of Ethiopia estimated that a loss of 1 cm of SD (about 100 ton of soil) reduces teff yield by 45 kg and 20 kg on red upland soils and low-lying Vertisols, respectively. Other studies in Ethiopia classified the susceptibility of soil to erosion as slightly susceptible, moderately susceptible and very susceptible with estimated productivity reductions of 1%, 2% and 7% per cm of topsoil loss, respectively (Sonneveld and Keyzer, 2003). Since scenario II is concerned with soil degradation facing smallholder farmers on slopping lands highly susceptible to water induced soil erosion, the output elasticity of SD is set at 0.07 whereas the output elasticity of Nitrogen from the first scenario is lowered by the amount of the output elasticity of SD. Other technology parameters (output elasticity of labour and capital for production) are carried over from the nutrient mining scenario. The scale parameter (A) is calibrated to reflect average input use and output level for the considered teff crop in the study area. Accordingly, the technology parameters used in scenario II are: b=0.1492, c=0.1194, d=0.07 and g=0.2280 representing output elasticity of labor, capital, topsoil depth and nitrogen, respectively. Other model parameter values used in the base run include: a nutrient augmentation coefficient of unity (β_1=1), nutrient extraction by crop ($\beta_2 = 29.15$ kg N per ton of harvested product), net nutrient depletion due to erosion and natural processes ($\beta_3 = 1.7$ kg N per ton of eroded soil), a discount rate of 9% and input and output prices discussed in section 6.3 of this chapter. The later parameter values with the exception of β_3 correspond with those used for the base run in the nutrient mining scenario.

Optimal steady state values of the choice variables (L_Y, K_Y, L_S and F), output (Y) and the resource stocks, N and SD for scenario II along with static solutions and average current practice for smallholder teff production in the Central highlands of Ethiopia are presented in Table 6.6. The dynamic steady state solutions are derived using equations (6.40-6.47) of this chapter.

A comparison of steady state optimal values of scenario II with the pure profit maximizing static solutions and current average farmer practices showed similar trends with scenario I in terms of the direction of effects but differed in the magnitude of the variables of interest. Output under the dynamic decision rule for the base run is 1.15 ton/ha compared to 0.42 ton/ha and 0.71 ton/ha under the static decision rule and current farmer practice, respectively. The optimal inorganic N input required to achieve and sustain output indefinitely under the dynamic decision rule is estimated at 52.5 kg/ha, higher by 265% and 117% over the requirements of the static decision and average current farmer practice, respectively. The level of labour and capital input use under the dynamic decision rule is also much higher than that of static decision rule. On the other hand, the net private benefit is highest for the static decision rule than the dynamic decision rule and current farmer practices suggesting static optimizers by ignoring long-term costs enjoy considerable savings in annul costs and hence ripe short-term benefits. The price static optimizers pay for ignoring long term costs, however, is lower soil quality and hence reduced future yields.

In this scenario the MUC of SD is calculated to be Birr 104.17 (USD 12.1) per cm of topsoil depth whereas the shadow price of N remained at Birr 15.74 per kg of N as in the nutrient mining scenario. It should be noted that considering the impact of SD in scenario II did not change the MUC of the nutrient stock (N) for we maintained the assumption of a unit value for the parameter of the nutrient augmentation function (β_1=1) which implies regardless of the N content of soil one unit external N input contributes exactly one unit of N into the nutrient pool. Considering a net soil loss of 35.3 ton/ha (0.353 cm of topsoil depth per annum) and net nutrient extraction of 56.7 kg/ha of N prevalent on slopping lands, the total user costs of top soil depth and soil Nitrogen would be 36.8 Birr per ha

Table 6.6. Optimal steady state solutions at two levels of natural rate of soil regeneration (Z) along with static solutions and current average farmer practice for the problem of nutrient mining and physical soil degradation (scenario II)

Item	Variable	Dynamic decision rule δ=9%, $\beta_1=1, \beta_2=29.15, \beta_3=1.7$		Static decision rule	Current average practice
		Z= 5 ton/ha	Z= 10 ton/ha		
1	Labor for production[1]	28	28	11	20
2	Labor for conservation[1]	112	112	0	27
3	Capital for production[2]	44.73	44.73	18	94
4	Inorganic fertilizer (kg/ha)	52.49	43.99	14.38	24.12
5	Output (teff grain ton/ha)	1.15	1.15	0.42	0.71
6	Net soil loss (ton/ha)[3]	0.00	0.00	48.36	35.31
7	Net N extraction (kg/ha)[4]	0.00	0.00	79.97	56.68
8	N stock (kg/ha)	301.55	301.55	N.A.	N.A.
9	SD stock (cm)	11.73	11.73	N.A.	N.A.
10	MUC of N (Birr/ha)[5]	15.74	15.74	15.74.	15.74
11	MUC of SD (Birr/cm)[6]	104.17	104.17	104.17	104.17
12	TUC of N (Birr/ha)[7]	0.00	0.00	1258.72	892.20
13	TUC of SD (Birr/cm)[8]	0.00	0.00	50.38	36.79
14	Net private benefit (Birr/ha)[9]	90.56	224.35	329.33	93.43
15	Net social benefit (Birr/ha)[10]	90.56	224.35	-979.77	-798.76

N.A.= Not applicable
[1]person-days/ha
[2]oxen hours/ha
[3]calculated based on equation (6.5)
[4]calculated based on equation (6.9)
[5]calculated based on equation (6.32)
[6]calculated based on equation (6.33)
[7]toal user costs of N is calculated by multiplying MUC of N (item 10) by the net N extraction (item 7)
[8]TUC SD is calculated by multiplying MUC of SD (item 11) by the net soil loss (item 6),
[9]gross benefit minus total costs
[10]net private benefit (item 14) minus TUC (sum of item 12 and 13)

and 892.2 Birr/ha, respectively. The TUC that current smallholder farmer practice entails on slopping lands where both soil nutrient mining and physical soil degradation (top soil depletion) co-exists would thus be 929 Birr/ha. These results, therefore, unambiguously showed that current soil fertility management and soil conservation practices on slopping lands are not only unsustainable but also involve tremendous social costs as evidenced by the high user costs.

A comparison of the dynamic optimal solutions of scenario II where both soil physical degradation (SD depletion) and nutrient mining jointly determin soil quality with the nutrient mining scenario (where soil erosion does not have a significant impact on soil quality) at a socially desirable steady state revealed interesting results. First, the optimal levels of the control variables (labor and capital for production and inorganic N inputs) required to achieve and sustain steady state output under scenario II are lower by about 13%, 12%, and 33%, respectively, over the nutrient mining scenario suggesting that the on-site effect of soil erosion (SD depletion) would be to shift the production possibility frontier inwards. Second, the net private and social benefits at steady state are considerably lower for scenario II compared to the nutrient mining scenario suggesting that failure to consider soil depth depletion under estimates costs or over estimates benefits. Third, optimal steady state N stock for scenario II is lower by 24% compared to the nutrient mining scenario suggesting soil quality and hence future productivity of the soil capital would be lower on slopping land than on low lying (bottom) plots. Fourth, the optimal conservation effort for scenario II would be higher by 400% over the nutrient mining scenario (112 man-days/ha against 28 man-days/ha) suggesting the private costs of soil erosion control would be tremendous on slopping lands. The above results confirm our main hypothesis that the nature of the soil degradation that smallholder farmers face on low lying (bottom) and slopping plots are quite different and that the optimal mix of soil fertility management and soil conservation practices required for sustainable use of the soil resources differ considerably. On low lying plots where the overriding problem is net extraction of nutrients, the optimal mix of soil management practice is to use more nutrient inputs with modest levels of conservation effort. On slopping plots where both nutrient mining and soil erosion are equally important sustainable use of soil resource require not only use of appreciable amounts of external nutrient inputs but also substantial investment in soil conservation effort. Therefore, given the high time rate of preference that smallholder farmers display, the lower average yields and that soil conservation investments are costly on slopping lands than low laying lands suggests that without appreciable public support it is unlikely that smallholder farmers take private initiatives to curb the alarming soil degradation currently prevailing on slopping lands.

6.4.4 Sensitivity analysis of the empirical nutrient mining and soil physical degradation control model (scenario II)

As is done for the nutrient mining scenario, optimal steady state solutions of scenario II are examined for its sensitivity to changes in parameter values and key assumptions. Sensitivity analysis results are provided in Tables 6.7 and 6.8.

Changing the coefficient of the augmentation function, (β_1), from 1 to 0.75, but still maintaining other parameter values at the base run level showed a similar effect as in scenario I. While the optimal steady state levels of production labor and capital, labor for conservation and the level of the nutrient stock remained at the base run level, the dynamic prices of N and SD increased by about 34% and 63%, respectively. The optimal level of inorganic N fertilizer required for maintaining the optimal output level indefinitely also increased by about 35% from 52 to 70 kg/ha suggesting increased inorganic N levels are needed to compensate for the less than perfect substitutability of inorganic N for natural soil N.

A 10% improvement in the output elasticity of N, all other parameter values kept at the base run level, raised the optimal levels of soil and non-soil inputs, inorganic N, output and the resource stocks whereas a similar percent fall in the output elasticity of N had the opposite effect. On the other hand, raising the output elasticity of SD from 0.07 to 0.1 while raised the optimal levels of production labor, capital, inorganic N and output modestly, it had a tremendous impact on the optimal levels of the resource stocks. Soil depth increased by about 177% from 11.7 cm to 32.5 and the nutrient stock by 45% from 302 to 438 kg/ha. Reducing the output elasticity of SD from 0.07 to 0.02, however, had the opposite effect. The simulation results, therefore, suggest that technical innovations that improve not only nitrogen efficiency but also reduce soil loss such as minimum tillage would be vital for sustainable use of soil resources on slopping lands. The fact that the optimal level of capital (oxen hours for cultivation) for scenario II is lower by 12% from 51 to 45 oxen-hrs/ha further suggest that agronomic practices involving minimum tillage or crops that require fewer plowings would be a viable option for sustainable use of soil resources on slopping lands.

As is true for the nutrient mining scenario, in scenario II as well, steady state optimal values are found to be highly sensitive to assumed discount rates. Raising the discount rate from 9% to 12%, keeping other parameter values at the base run level, reduced the optimal levels of non-soil inputs, output and the resource stock appreciably. In particular, the stock of SD reduced from 11.7 cm to 6.5 cm and the nutrient stock from 302 to 186 kg/ha unambiguously indicating smallholder farmer practices are unsustainable. Lowering the discount rate say from the base run level to 6% would have the opposite effect: raised the optimal steady state levels of labor and capital use for production, inorganic N fertilizer, the resource stock and output. Note worthy is that lowering the discount rate by only three percentage points (from 9% to 6%) increased the optimal N stock from 302 kg/ha to 598 (higher by 98%), the optimal stock of SD from 11.7 cm to 27 cm (higher by 130%) and net benefits from 91 Birr/ha to 473 Birr/ha (higher by 423%). The above simulation results once again attest measures that reduce smallholder farmers rate of time preference such as improved land tenure security, access to credit and actions targeted at reducing poverty would raise the future worth of soil resources thus provide incentives for the adoption of soil fertility and conservation measures which inurn contribute to a more sustainable use of soil resources.

Table 6.7. Sensitivity analysis with respect to changes in the coefficients of the augmentation function and elasticity of output with respect to N fertilizer and SD, scenario II

Variable	Base run δ=9% $\beta_1=1$ $\beta_2=29.15$ $\beta_3=1.7$ Z=5	Change in G(F) δ=9% $\beta_1=0.7$ $\beta_2=29.15$ $\beta_3=1.7$ Z=5	Change in output elasticity of N (g) δ=9% $\beta_1=1$ $\beta_2=29.15$ $\beta_3=1.7$ Z=5		Change in output elasticity of SD (d) δ=9% $\beta_1=1$ $\beta_2=29.15$ $\beta_3=1.7$ Z=5	
		25% fall	10% rise	10% fall	d=0.1	d=0.02
Production labor [1]	28	28	41	20	41	18
Conservation labor[1]	112	112	112	112	112	112
Production capital[2]	44.73	44.73	65.10	32.08	64.91	28.62
Inorganic fertilizer[3]	52	69.98	65.17	44.50	65.39	42.86
Output (teff grain ton/ha)	1.15	1.15	1.64	0.84	1.64	0.77
N resource stock (kg/ha)	301.55	301.55	482.69	194.60	437.55	192.92
SD resource stock (cm)	11.73	11.73	12.88	10.84	32.47	0.98
MUC[4] of N (Birr/ha)	15.74	20.99	15.74	15.74	15.74	15.74
MUC of SD (Birr/cm)	104.17	169.83	120.05	90.15	113.61	63.72
Net benefit[5]	90.56	-184.82	554.55	-206.49	568.46	-258.61

[1]person-days/ha

[2]oxen hours/ha

[3]kg/ha

[4]marginal user cost

[5]Birr/ha

Simulation results of a 25% increase/decrease in the price of inorganic N and the price of output exhibited a similar effect on the optimal input and output levels as in the nutrient mining scenario. While a fall in the price of inorganic N and a rise in the output increased the optimal input levels of labor and capital for production, inorganic N, the resource stock and output, a rise in the price of inorganic N and a fall in output price showed the opposite effect. The only difference observed is that lowering the price of inorganic N reduced the shadow price of the nutrient stock whereas an increase in output price did not affect the shadow price of the nutrient stock. The policy implications, however, remained the same. Policies targeted at improving market access (improvement in road networks), improving the efficiency of existing input and output markets (reduce transaction costs) would be vital for sustainable use of soil resources.

Table 6.8. Sensitivity analysis with respect to changes in the discount rate, fertilizer and output price for the scenario II (nutrient mining and physical degradation)

	Base run	Change in discount rate		Change in inorganic N price (W_F)		Change in output price (P_Y)	
	δ=9%	δ=6%	δ=12%	25 % fall	25 % rise	25% rise	25 % fall
Production labor [1]	28	37	23	38	21	52	12
Conservation labor[1]	112	112	112	112	112	112	112
Production capital[2]	44.73	59.11	36.71	60.56	33.82	82.95	19.20
Inorganic fertilizer[3]	52.49	62	47	60	47	65	41
Output (grain ton/ha)	1.15	1.53	0.93	1.45	0.93	1.63	0.71
Stock of N (kg/ha)	301.55	598	186	544	182	559	129
Stock of SD (cm)	11.73	26.96	6.50	15.88	8.87	21.75	5.04
MUC of N (Birr/ha)	15.74	15.74	15.74	11.81	19.68	15.74	15.74
MUC of SD (Birr/cm)	104.17	95.97	110.05	109.07	99.27	126.31	82.04
Net private benefit	90.56	473.25	-120.75	585.21	-278.39	1082.86	-565.57
Net social benefit	-1078.11	-533.26	-1401.39	-574.47	-1434.46	-219.46	-1557.43

Note: all parameter values other than the discount rate are set at the base run level
[1]person-days/ha
[2]oxen hours/ha
[3]kg/ha

6.5 Concluding summary

This chapter applied the analytical optimal control model developed in chapter four to the soil degradation problem facing smallholder farmers in the Central highlands of Ethiopia. First, recognizing smallholder farmers manage several small plots of land scattered across micro-environments and that the nature of soil degradation on low lying (bottom lands) is different from the soil degradation problem on sloping lands (upland plots), the study developed two versions of a dynamic control model for the respective soil degradation scenarios. The analytical control model developed in chapter four was then empirically specified for the two soil degradation scenarios and solved for dynamic (socially desirable steady state) and static profit maximization solutions. Results for the dynamic and static solutions were compared with average current farmer practices.

Four major conclusions are drawn from the optimization results. First, steady state optimal output and input levels under the dynamic decision rule are found to be significantly higher than the static solutions suggesting the static decision rule is sub-optimal. Second, current farmer practices involve a net nutrient (N) extraction of 16.2 kg/ha from bottomlands and 56.7 kg/ha from slopping lands entailing a total soil user cost of Birr 255 per ha and Birr 928 per ha, respectively, suggesting smallholder farmers discount the future heavily (display a high rate of time preference) and hence over exploit the resource stock for the resource is considered worth more now than in the future. Third, the fact that current soil nutrient inputs and conservation efforts are well above the requirements of the static decision rule but much lower than the dynamic steady state solutions suggest that smallholder farmers consider some of the externalities of soil degradation. The policy implication from one and two is that the social gains from better utilization of soil resources are tremendous and government assistance that unlocks the private incentives and help smallholder farmers adjust their input use levels towards the socially desirable steady state levels would be desirable not only to improve profitability of smallholder agriculture but also attain sustainable use of the soil capital.

Fourth, a comparison of steady state dynamic solutions of scenario I where nutrient stocks is the sole determinant of soil quality with scenario II where both nutrient stocks and rooting depth impinge on soil quality confirm the main hypothesis that the socially optimal path of soil use not only diverged from the private optimal path but also depends on the nature of soil degradation smallholder farmers face on their plots. The policy implication is that in the highlands of Ethiopia where smallholder farmers manage multiple plots of heterogeneous soil quality and where perception of soil degradation is a function of plot characteristics soil conservation projects and programs need to consider plot heterogeneity in program design and implementation.

Results of the sensitivity analysis showed that model results are sensitive to changes in model parameter values and key assumptions. A rise in the discount rate lowered steady state optimal input levels, output and the resource stock whereas a lower discount rate have the opposite effect suggesting measures that raise the future worth of soil resources would be crucial to induce smallholder farmers to adopt soil conserving farming techniques. Sensitivity analyses with respect to changes in output and N fertilizer price also showed steady state optimal input and output levels increased with a fall in the price of inorganic N and a rise in the price of output suggesting improved access to markets would contribute to a more sustainable use of soil resources.