The dynamics of soil degradation and incentives for optimal management in the Central Highlands of Ethiopia

By

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Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy: Environmental Economics in the Department of Agricultural Economics, Extension and Rural Development, Faculty of Natural and Agricultural Sciences,
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February 2007

Dedication

To my mother, Zemamu Gebremedhin; my wife, Hiwot Hailu and my daughter, Lydia Chilot

Declaration

I, the under signed, hereby declare that this thesis, which I submit for the degree of PhD in Environmental Economics at the University of Pretoria is my own work and has not been previously submitted for a degree at another university.

ACKNOWLEDGEMENTS

This thesis would have not been completed had it not been to the support and contributions of many individuals and institutions. My special thanks go to my supervisor, Prof. Rashid Hassan for his guidance and relentless support. His persuasiveness, keen interest and challenges sharpened my thinking and I say once more thanks.

I am grateful to Drs. Ramos Mabugu, Alemu Mekonen and Kerk Hamilton for their advice and invaluable comments during the planning stage of the research. Thanks also due to Dr. James A. Benhin for reading part of the early drafts of the thesis and making valuable suggestions.

I would like to thank the Ethiopian Institute of Agricultural Research (EIAR) for supporting my study through a World Bank supported Agricultural Research and Training Project (ARTP). The financial support of CEEPA is also dully acknowledged. I also thank Professor Johan Kirsten, Head of Department for the administrative and moral support. The contributions of Mrs Zuna Botha and Dalene du Plesis in maintaining a pleasant working environment has immensely contributed to the completion of this study.

Thanks are also extended to my colleagues and friends at Holetta Research Center for the multifaceted assistance during the course of the data collection stage and beyond. Among others the assistance of Dr. Negussie Alemayehu, Center Director and the socio-economics staff, namely, Agagie Tesfaye, Aselef Teshome and Takle Mebratu were commendable. I am also grateful to Dr. Woldeysus Sinebo, Dr. Asgelil Debabe, W/o Workalem Berihun and W/o Missa Demise for the invaluable assistance provided to my family.

This thesis would have not bean realized without the unprecedented support, love and care of my wife Hiwot Hialu, my sisters, Raheal, Yeshi, Yabune, Belyanesh, Adina, Tiruembet and my brother Amsalu. Special thanks is due to my mother, Zemamu

Gebremedhin and my daughter, Lydia, who, despite being on the opposite side of the age spectrum raised same questions, had similar wishful thinking and difficulties of comprehending my extended absence. The motivation and encouragement of colleagues and friends at the University of Pretoria and its environs was instrumental for the completion of my thesis work. These are Patrick Birunji, Benjamin Banda, Jethro Zuwarimwe, Yamane Fesihaye, James Juana, Enid Katungi, Ameha Sebsibe, Tedie O. Nakhunma, Oyenuga Oyenike, Mampiti Elizabeth Matete, Glwadyes Gbetbouo, Hailu Beyene, Legesse Wolde, Amsal Tarekenge, Abebe Damte and many others.

Finally I thank my Lord, Jesus, who nurtured me through all the years and provided me the patience, strength and wisdom required for completing this study.

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ABSTRACT

In Ethiopia, as in the rest of sub-Saharan Africa, soil degradation (decline in soil quality due to topsoil loss and net nutrient extraction) has become the most important natural resource problem imposing on-site costs to individual farmers in terms of reduced yield and off-site costs to society as a result of externalities. Excessive soil loss rates reaching over 100 tons/ha on croplands are not uncommon. Much worse, the amount of nutrients extracted from the soil through cropping is estimated to be several folds the nutrient inputs added to the soil in the form of organic and inorganic nutrients. Consequently, per capita food production, income and savings have been falling.

Nonetheless, despite the seriousness of soil degradation problems and its negative consequences on food security and income to individual households and the nation at large, the magnitude of the threat that soil degradation poses on current as well as future income and how best to address the problem is not well known. The few available estimates based on static models that do not account for the inter-temporal use of the soil capital indicate the importance of the soil degradation problem but could not provide the full costs that continued soil degradation will have on the country's economic development. Furthermore, the attention provided to the analysis of soil conservation adoption and soil nutrient management practices to date is minimal. This thesis, therefore, using an inter-temporal optimisation framework analysed the tradeoffs of soil

use that smallholder farmers' face in their production decisions. Also, using econometric models that account for simultaneity of choices and plot level survey data, the thesis analysed the determinants of soil fertility and soil conservation adoption decision behaviour of smallholder farmers in the Central highlands of Ethiopia. For the former purpose, the study developed a dynamic analytical control model, derived optimality conditions, solved steady state dynamic and profit maximizing static solutions and then compared results with current average farmer practices. For the latter purpose, multinomial logit models for discrete dependent variables involving multiple choices, Heckman's two-step and Tobit regression models for the censored continuous dependent variables of intensity of inorganic fertilizer and stone/soil bunds, respectively, were employed.

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 signifying that 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. Third, although current soil nutrient inputs and conservation efforts are lower than the dynamic steady state solutions it is well above the requirements of the static decision rule. Smallholder farmers, therefore, appears to have private incentives and hence consider some of the externalities of soil degradation. These findings suggest 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 input use levels towards the socially desirable steady state levels would be desirable to improve profitability of smallholder agriculture and attain sustainable use of the soil capital. Fourth, a comparison of steady state dynamic solutions where Nitrogen stock is the sole determinant of soil quality with a case where both Nitrogen stock 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. 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 should consider plot heterogeneity in program design and implementation.

The sensitivity analysis of the steady state dynamic solutions showed that 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. Measures that raise the future worth of soil resources would, therefore, be crucial to induce smallholder farmers to adopt soil conserving farming techniques. Similarly a rise in output price and a fall in the price of inorganic N fertilizer would have the impact of raising steady state optimal input and output levels whereas a fall in output price and a rise in the price of inorganic N would have the opposite effect. Policies aimed at improving market access and efficiency of existing input and output markets that ensure the delivery of inorganic fertilizers at the right time, product mix and reasonable price, therefore, are likely to increase the use of inorganic fertilizers and soil conservation practices which ultimately contribute to a more sustainable use of soil resources.

The econometric analyses of soil fertility and soil conservation adoption behavior of smallholder farmers provided a number of findings of policy relevance. First, the study showed the importance of farmer education in raising the likelihood of using most of the soil fertility management (SFM) practices as well as intensity of use of inorganic fertilizer and stone/soil bunds suggesting investment in education are indispensable to reducing soil degradation and improve farm income. Second, livestock, a proxy for the wealth position of households, is positively and significantly related with the likelihood of using inorganic fertilizers and integrated soil fertility management (ISFM) practice. Livestock also has a positive and significant effect on the intensity of use of inorganic fertilizers and stone/soil bunds. Households with livestock (particularly oxen) utilize not only their land more productively but also lease in additional land from fellow farmers, take the production and marketing risks associated with using inorganic fertilizers and stone/soil bunds. Improving smallholder farmers' access to better livestock husbandry techniques particularly veterinary services coupled with measures that increase oxen ownership (individually or collaborative) would be vital to enhance adoption of soil fertility and conservation practices. Third, project assistance in sharing the initial investment costs of soil and water conservation (SWC) structures and access to extension are found to be important determinants of the intensity of SWC and inorganic fertilizers as well as the likelihood of using ISFM technologies suggesting government assistance is vital in improving adoption and hence contribute to more sustainable use of soil resources. Fourth, the likelihood of using manure, ISFM and stone/soil bunds is found to be significantly higher on owned lands than rented in or sharecropped plots suggesting that improved tenure security is a precondition for households to engage in soil fertility management and soil conservation practices that have a long gestation period. Fifth, plot size and number of plots, a proxy for farm size, are positively and significantly related with the likelihood of using all types of SFM but animal manure. Land redistribution in the already degraded and land scarce highlands, therefore, not only contribute to land fragmentation but also by raising the fixed costs of operating micro (very small) and dispersed plots further undermine sustainable farming and increase nutrient mining. Sixth, while access to institutional credit for the purchase of inorganic fertilizers enhanced both incidence and intensity of inorganic fertilizers it has a detrimental effect on the use of stone/soil bunds. This is an important tradeoff that should be considered seriously in policy formulation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND ABBREVATIONS

ACRU	Agricultural Catchement Research Unit
ADLI	Agricultural Development Led Industrialization
AGNPS	Agricultural Non-point Source Model
AM	Animal Manure
ANSWERS	Arial Non-Point Source Watershed Environment Response Simulation
CBH	Cost-Benefit Analysis
C-D	Cobb-Douglas
CLAD	Censored Least Absolute Deviations
CREAMS	Chemical Runoff and Erosion from Agricultural Management Systems
CSA	Central Statistical Authority, Ethiopia
DAP	Diamonium Phosphate
EI	Erodibility Index
EPID	Extension and Project Implementation Department
EPL	Erosion Productivity Loss
FAO	Food and Agricultural Organization
FDRE	Federal Democratic Republic of Ethiopia
FFHC	Freedom from Hunger Campaign
FOCs	First Order Conditions
GDP	Gross Domestic Product
HARC	Holeta Agricultural Research Center
IGF	Inorganic Fertilizer
IIA	Independence of Irrelevant Alternatives
ISFM	Integrated Soil Fertility Management
LAD	Least Absolute Deviations
LP	Linear Programming
LR	Legume Rotations

MEDaC	Ministry of Economic Development and Cooperation
MFD	Ministry of Finance and Development, Imperial Ethiopian
MLE	Maximum Likelihood Estimates
MNL	Multinomial Logit
MNP	Multinomial Probit
MOA	Ministry of Agriculture, Ethiopia
MPP	Minimum Package Program
MUC	Marginal User Cost
N	Nitrogen
NGOs	Non-Governmental Organizations
OLS	Ordinary Least Square
PA	Peasant Association
PRA	Participatory Rural Appraisal
RSLE	Revised Soil Loss Equation
SCRP	Soil Conservation Research Project
SD	Soil Depth
SF	Seasonal Fallowing
SFM	Soil Fertility Management
SLEMSA	Soil Loss Estimation Model for Southern Africa
SSA	sub-Saharan Africa
SUEST	Seemingly Unrelated Estimation
SWC	Soil and Water Conservation
TGE	Transitional Government of Ethiopia
TLU	Tropical Livestock Unit
US	United States
USD	United States Dollar
USLE	Universal Soil Loss Equation
VCE	Variance-Covariance
WEPP	Water Erosion Prediction Project
WFP	World Food Program of the United Nations

Chilot Yirga Tizale was born at Woken, North Gonder Zone of Ethiopia in 1964. He earned a BSc degree in agricultural economics in 1986 from the Alemaya University of Agriculture (AUA). Soon after graduation, Chilot joined the then Institute of Agricultural Research (IAR) now the Ethiopian Institute of Agricultural Research (EIAR) as a junior researcher. After working for 4 years he rejoined the AUA and obtained MSc degree in the field of Agricultural Economics in 1994. Currently he is working in the same institution as a senior researcher.

In his thesis, the dynamics of soil degradation and incentives for optimal management in the central Highlands of Ethiopia, he addressed the very important problem of sustainability of current soil management practices and their long-term consequences for the welfare of rural people in the Ethiopian Highlands. Recognizing the inter-temporal nature and dynamic costs associated with the extraction of exhaustible natural resources such as soils, he modeled the dynamics of soil resource extraction and evaluated the consequences of ignoring this dimension for policy design and optimal land management decisions. In the modeling approach developed for dealing with the problem of exploiting non-renewable resource stocks he was able to extend earlier modeling attempts by incorporating innovative extensions to deal with the irreversible soil physical degradation through loss of topsoil as a result of erosion, which normally are ignored in the literature. The study also analyzed determinants of farmers' decisions to adopt soil conservation and fertility management techniques. The results of the study generated useful information for improved policy for optimal soil management and development for the promotion of appropriate smallholder farming technologies. So far one article in an accredited journal has been published and two manuscripts are under review for publication in international journals.

CHAPTER I: INTRODUCTION

1.1 Background and motivation

Land degradation as a result of soil erosion and soil nutrient mining and their consequent negative effects on productivity, food security and well being of rural population are considered a fundamental problem in most sub-Saharan African (SSA) countries (Lal, 1995; Bojo, 1996; Brekke et al., 1999; Pagiola, 1999; Sonneveld and Keyzer, 2003; Nakhumwa, 2004).

In Ethiopia, soil degradation is recognized as one of the most important natural resource problems imposing on-site costs to individual farmers in terms of reduced yield and off-site costs to society as a result of externalities (Hurni, 1993; Sutcliffe, 1993; Bojo and Cassells, 1995; Shiferaw and Holden, 1998; Pender et al., 2001). A number of studies have shown that current soil loss rates on croplands stand between 42 and 100 ton/ha/year in the highlands leading to a productivity decline between 0.2 and 1.8 per cent per year (FOA, 1986; Hurni, 1993; Sutcliffe, 1993; Bojo and Cassels, 1995). Sutcliffe (1993) further noted that if soil erosion continues at current rates, over 6 million hectares of additional cropland and pasture in the Ethiopian highlands might become unusable by 2010. Similarly, estimated soil nutrient losses for the highlands of Ethiopia are high, exceeding 80 kg of N, P_2O_5, and K_2O per cultivated hectare (Stoorvogel and Smaling, 1990).

In Ethiopia where agriculture accounts for 50 per cent of GDP, 90 per cent of exports and 85 per cent of employment, agricultural intensification is a prerequisite for economic development (MEDaC, 1999). However, soil degradation has become the basic challenge constraining smallholder farmers from achieving an acceptable level of food security. Improved agricultural technologies (improved crop varieties, commercial fertilizers, better agronomic practices and pest control measures) have been promoted among smallholder farmers by government and non-government organizations (NGOs) in an attempt to address the declining agricultural productivity and improving food security.

However, despite these efforts, adoption of agricultural technologies by smallholder farmers across the country has remained below expectations (Yirga et al., 1996; Demeke et al., 1997; Alene, et al., 2000; Croppenstedt et al., 2003). As a result, the productivity of Ethiopian agriculture has remained one of the lowest in the world. Yield per hectare of cereals remained low at 1.2 tons per hectare compared with the global average of 4.0 tons per hectare (FAO, 1998). As a consequence, food availability per person has progressively declined (Zegeye and Habtewold, 1995; MEDaC, 1999).

Recognizing that the benefits from improved agricultural technologies would not be realized unless accompanied by soil conservation measures and prompted by the 1974 drought that caused devastation to the rural population, the government assisted by external donors launched a major public soil conservation (soil and stone bunds) works under the food-for-work program since the 1970's. However, adoption of both soil conservation and soil fertility enhancing practices such as commercial fertilizers have remained low (Yirga et al., 1996; Gebre Michael, 1999; Shiferaw and Holden, 1998; Gebremedhin and Swinton, 2003; Croppenstedt et al., 2003).

Farmer incentives to invest in soil conservation and soil fertility enhancement practices in Ethiopia and elsewhere in SSA countries have been constrained by a combination of unfavorable biophysical environment, population pressure, the institutional set up and short-term household objectives (Reardon and Vosti, 1995; Bojo and Cassells, 1995; Clay et al., 1998; Shiferaw and Holden, 1998; Pender et al., 2001; Sonneveld and Keyzer, 2003).

Population pressure has often been mentioned as one of the factors responsible for land degradation in Ethiopia (Grepperud, 1996; Pender et al., 2001; Sonneveld and Keyzer, 2003). The population of Ethiopia grew from 53 million in 1992 to 67.2 million in 2003 and expected to reach 129 million by 2030 (CSA, 2004). While population has continued to grow, growth in agricultural production declined from 0.7 per cent during the 1970-80 periods to 0.4 per cent in the 1980-92 period (World Bank, 1994)**.** The high population pressure in the Ethiopian highlands has led to land fragmentation as the available land have been redistributed to the increasing population over generations. Another issue linked to the soil degradation problem, the low level of adoption of soil conservation technologies and lack of interest in long term soil fertility maintenance practices is the insecurity of land tenure in Ethiopia (Adal, 2003; Rahmato, 2004). Prior to 1974 land reform, land tenure in Ethiopia was based on a feudal system where few landlords owned much of the land while the majority of farm households were tenants. Following the 1974 land reform, the then socialist government nationalized all rural land, ended all forms of tenancy, and distributed land to farm households based on family size (Stroud and Mekuria, 1992; Rahmato, 1984; Adal, 2000). However, farmers had only restricted usufruct rights but were not allowed to transfer their holdings in any form (inheritance, renting, share-cropping or gift). Land was re-distributed frequently in order to reduce landlessness as well as to address land quality differences until 1991. Following the fall of the socialist government in 1991, the new government introduced a series of political and economic reforms but land remained the collective property of all the people of Ethiopia under the custody of the government. Insecurity of land tenure has thus been and continues to be a major problem in Ethiopia.

Agricultural development policies have often been blamed to be unfavorable for the sustainable use of natural resources in Ethiopia. Domestic agricultural policies in the 1970s and 1980s discriminated against rural households by suppressing producer prices and forcing farm households to deliver a portion of their produce to the government controlled marketing institutions providing disincentive to the adoption of improved crop production as well as soil conservation practices (Franzel et al., 1992; Adunga and Demeke, 2000). The presumption that the country's food problem could be addressed through a quick fix of technological solutions also prompted government and donor agencies alike to adopt a technology transfer approaches focusing on short-term programs such as the development and transfer of improved crop production technologies. Besides, smallholder farmers primarily concerned with securing adequate food for their family immediate needs use low-external inputs and erosive farming techniques, which do not only mine the soil but also jeopardize the nations long-term food production ability. A recent study by Holden et al. (1998) suggested that smallholder farmers in SSA have very high rates of time preference, which partly explains smallholder farmers' reluctance to engage in long-term soil fertility and soil conservation practices.

1.2 Problem statement

Despite the seriousness of soil degradation problems (decline in soil quality due to water induced topsoil loss and net nutrient extraction) prevalent in Ethiopia and SSA countries, limited information and analyses have been carried out on the economic impact of soil degradation (Shiferaw and Holden, 2001; Brekke et al., 1999; Sonneveld and Keyzer, 2003). Knowledge of the technical relationship between soil loss and decline in crop yields was considered sufficient for formulation of sound conservation policy and hence the neglect of economic aspects of soil degradation control. Consequently, until recently, ecological effectiveness and technical simplicity had been a guiding principle in the design of soil conservation practices and policies in SSA including Ethiopia (Kapple, 1996).

As noted earlier, in SSA including Ethiopia, soil degradation is a pervasive problem posing a threat to current and future income and welfare of smallholder farmers as well as to national food security (Hurni, 1993; Sutcliffe, 1993; Bojo and Cassells, 1995; Bishop, 1995; Eaton, 1996; Shiferaw and Holden, 1998; Sonneveld and Keyzer, 2003). Farm households bear on-site costs associated with the control of soil degradation practices but gain very little from the off-site benefits generated as a result of their actions. These households may not be willing to invest in soil conservation suggesting the existence of a divergence between the private and social objectives concerning optimal levels of soil conservation. This divergence arises not only due to externalities but also because of insecure land tenure and market imperfections and limited access to input and output markets, credit, off-farm employment and information (Barbier and Burgess, 1992; Barbier, 1995; Holden et al., 1998; Holden and Shiferaw, 2004; Rahmato, 2004). It has been postulated in the economic literature that an individual farmer might not adopt the optimal path of soil use that a social planner would because the farmer's rate of time discount exceeds that of the social planner (McConnell, 1983; Reardon and Vosti, 1995;

Bishop; 1995; Barbier, 1995; Holden et al., 1998). The high time preference displayed by smallholder farmers is believed to be associated with poverty, risk aversion behavior and insecure land tenure (Barbier, 1995; Bishop, 1995; Shiferaw and Holden, 1999).

Economic theory also asserts that farmers in a perfectly competitive market use land in such a way that equates the marginal private cost of production with the marginal private benefit. In the presence of externalities, however, the social marginal costs will be greater than the marginal private cost of agricultural production realized by farmers suggesting that from society's point of view the soil capital is over utilized and that private and social optima diverge.

As has been pointed out, empirical studies that quantify and analyze the divergence between the private and social optima in the use of soil capital are quite rare in SSA including Ethiopia. Admittedly, an agricultural country such as Ethiopia need to adopt a long term and dynamic perspective to the soil erosion and soil-mining problem if the country has to conserve its fragile soil resources. Policy prescriptions based on short-term assessment of costs and benefits are highly unlikely to be optimal. Accordingly, the present study adopted a dynamic optimization framework in order to assess the inter-temporal trade-offs (the true social costs of soil loss relative to the value of output expected) that farmers face in their production decisions. The study therefore aims to determine and compare optimal levels of input use and production when the dynamic costs of soil erosion and mining are taken into account with static solutions when dynamic costs are ignored.

As argued above, use of organic and inorganic fertilizers and soil conservation practices remain low among smallholder farmers in Ethiopia. This study also attempts to analyze the incidence and intensity of use of alternative soil conservation and soil fertility management technologies and identify the factors influencing smallholder farmers' adoption decisions across agro-ecologies, farming systems, administrative boundaries and socio-economic groups.

The study aims to contribute to improved policy formulation and design through the identification of socio-economic factors that has constrained the adoption of soil conserving and soil nutrient enhancing practices by smallholder subsistence farmers. Knowledge about the dynamic costs of soil degradation is also useful for correcting the national income accounts to better reflect sustainable income.

1.3 Objectives of the study

This study has two main objectives. The first is to analyze the effect of ignoring the dynamic cost of soil erosion and soil nutrient mining in production decisions and resource allocation and use in Ethiopia. The second main objective is to analyze the incidence and determinants of intensity of use of soil conservation and soil fertility management practices in Ethiopia. Specific research tasks to be pursued under these two main objectives are:

1. Derive and compare optimal resource use and production levels under static and dynamic decision environments with respect to soil erosion and mining.
2. Measure the dynamic cost of soil erosion and the implications of not accounting for soil resource depletion on the country's economic welfare.
3. Assess the incidence and intensity of use of improved as well as indigenous soil fertility and soil conservation practices employed by smallholder farmers in the Central Highlands.
4. Examine the factors that condition farmers' choice (rate and intensity) of improved soil conservation measures and soil fertility management options in the Central Highlands.
5. Analyze policy implications and suggest ways of improving soil degradation control and soil fertility management practices.

1.4 Approaches and methods of the study

This thesis provides an analysis of the socio-economic aspects of soil degradation as it applies to smallholder subsistence farmers in the central highlands of Ethiopia. It employs mainly two analytical techniques to attain the stated objectives. The study first develops an optimal control model and then applies the model to quantify and compare the optimal levels of soil degradation under dynamic and static conditions. Second, the study estimates the incidence (rate) and intensity of use of soil conservation and soil fertility management practices to illustrate the spatial pattern of adoption across farming systems and socioeconomic groups. Technology adoption and diffusion models are used to analyze the factors that condition the rate and intensity of use of soil fertility and soil conservation practices by smallholder farmers in the Central Highlands of Ethiopia.

1.5 Organization of the thesis

The thesis is organized into nine chapters. The next chapter (chapter II) presents an over view of the agricultural setting of Ethiopia and its soil resources. Chapter III reviews the relevant literature on the economics of soil fertility management and soil conservation practices with due attention to the approaches used to measure and model economic costs and benefits of soil use and conservation. Chapter IV presents the study approach for modeling the dynamics of optimal use and extraction of the soil capital in Ethiopia. Chapter V is dedicated to describing the study locations, the research design and socio-economic characteristics of the sample households. The optimal control model developed in chapter IV is empirically specified and applied to the situation of smallholder farmers in the highlands of Ethiopia in chapter VI. Chapters VII and VIII are concerned with the analysis of the soil fertility and soil conservation adoption behavior of smallholder farmers in the highlands of Ethiopia. While chapter VII presents the analytical framework adopted by the study, chapter VIII applies the econometric models specified in chapter VII and discusses the results. The last chapter, chapter IX, provides a summary of the research problem, the study approach, the main findings and implication for policy and further research.

CHAPTER II:OVER VIEW OF THE AGRICULTURAL SECTOR, SOIL RESOURCES AND SOIL DEGRADATION IN ETHIOPIA

This chapter presents an overview of the agricultural sector and the conditions of soil resources in Ethiopia. The first section provides a summary of the performance of the agricultural sector focusing on trends in production and productivity. Section two describes the dominant soil resources of Ethiopia; examines the extent and severity of soil degradation; documents the effects of soil degradation on the development of the agricultural sector; and assesses the research and extension interventions implemented in the country to contain soil degradation. The third section offers an assessment of the economic policy environment that has shaped past and current efforts to contain soil degradation and bring about sustainable agricultural development in Ethiopia. The last section concludes by providing a summary.

2.1 Performance of the agricultural sector

Ethiopia with 1.12 million square km of total area is one of the largest countries in Africa exhibiting a considerable geographical variation with altitudes ranging from 125 meters below sea level in the Danakil to 4620 meters above sea level in the peaks of the Semien mountain ranges. Ethiopia is the second most populous country in Africa with 67.2 million people, of which about 89 per cent reside in rural areas (CSA, 2004). While about 66 per cent of the land is considered to be suitable for agriculture, only 16.5 million ha are estimated to be under cultivation in any one year (MEDaC, 1999). However, about 88 per cent of the human and 75 per cent of the livestock population are concentrated in the highlands, areas higher than 1500 meters above sea level, constituting 44 per cent of the land area of Ethiopia. The highlands also constitute about 95% of the cultivated area (Kruger, et al., 1996). Though land and labor are the two most abundant resources vital for its economic development, the fast growing population, currently estimated to be increasing at 2.9 per cent, and the current land use appear to be in disharmony threatening the sustainable use of its natural resources particularly that of land which forms the bases of livelihood for the majority of the population.

Poverty is pervasive in Ethiopia with an estimated 44 per cent of the population living under the poverty line (FDRE, 2000; World Bank, 2004). Economic growth has been stagnant, even declining during the socialist regime, which ruled the country from 1974 to 1991. For instance during the period 1982 to 1992, per capita gross domestic product (GDP) declined at a rate of 2.4 per cent per annum. However, following regime change and introduction of economic policy reforms in the 1990's, per capita GDP grew by an average rate of 5.5 per cent per annum (Table 2.1).

Agriculture is the mainstay of the economy contributing about 50 per cent of the gross domestic product (GDP), 85 per cent of the employment and 90 per cent of the export earnings (MEDaC, 1999). Agricultural products: coffee, oil seeds, pulses, hides and skins and recently chat (Catha edulis, a stimulant crop) constitute about 90 per cent of the export earnings. Coffee is the single most important foreign currency earner contributing about 60 per cent of the export earnings in any one year (MEDaC, 1999).

Despite its importance, the performance of the agriculture sector has been dismal. While population grew by 2.9 per cent per annum between 1980 to 1990, value added in agriculture and allied activities at 1980 constant factor cost grew by about 1.3 per cent which in effect meant a decline of 1.6 per cent per annum. This dismal performance of the sector was partly attributed to the poor policies of the socialist oriented military regime. The performance of the agricultural sector, however, did not improve much with the demise of the military regime. Since 1992, value added in agriculture and allied sectors have shown a modest growth of 2.8 per cent per annum (Table 2.1). And yet, apart from the services sector, which exhibited relatively better and consistent growth in the post reform period, the relative share of agriculture and industry of total GDP remained largely unchanged (Figure 2.1). The fact that there has not been any perceptible growth in the other sectors meant that agriculture will continue to play a dominant role in the country's future economic development. Consequently, improvements in the agricultural sector will have a strong bearing on the country's economic growth. Conversely, failure to stimulate meaningful growth in the agricultural sector based on judicious use of the natural resources such as land might result in declining national income, reduced savings, worsening food security, which in turn perpetuates poverty.

Table 2.1. Average annual growth rate for key economic indicators in Ethiopia, (1982-2002)

	1982-92	1992-02	2001	2002
GDP	0.7	5.5	7.7	5.0
GDP per capita	-2.4	3	5.2	2.7
Export of goods and services	-3.2	12.6	-1.6	7.7
Agriculture	1.3	2.8	11.5	4.5
Industry	-2.9	6.1	5.8	5.4
Services	1.8	8.3	4.6	5.5
Gross domestic investment	-1.8	10.3	27.4	17.4

Source: World Bank (2004)

In Ethiopia, smallholder subsistence farmers cultivating small land holdings dominate the agricultural sector. Smallholder farmers cultivate 95 per cent of the cropped area; produce more than 90 per cent of the agricultural output, and 98 per cent of the coffee. Large-scale commercial private and state farms, on the other hand, produce 6 per cent of the food and 2 per cent of the coffee (MEDaC, 1999). Cereal production accounting to about 73 per cent of the cropland and nearly 70 per cent of the caloric intake of the population dominate smallholder production, followed by pulses, oil seeds and horticultural crops (CSA, 2004). Average farm sizes vary across the country depending on population density, agro-ecology (highland vs. lowland) and production system (pastoralism vs. sedentary agriculture) but are generally very small and declining over time. For instance in 1995, of those households who have access to some type of farmland, 62.9 per cent owned less than 0.5 ha of land against 69.1 per cent in the year 2000 (CSA, 2004). Nonetheless, despite the significance of smallholder farming in the country's agriculture in terms of food production, employment and foreign exchange earnings, the attention provided to the sector until recently had been minimal. Until the late 1990's, much of the capital expenditure[1] had been targeted to the promotion of large-scale commercial farming (MEDaC, 1999).

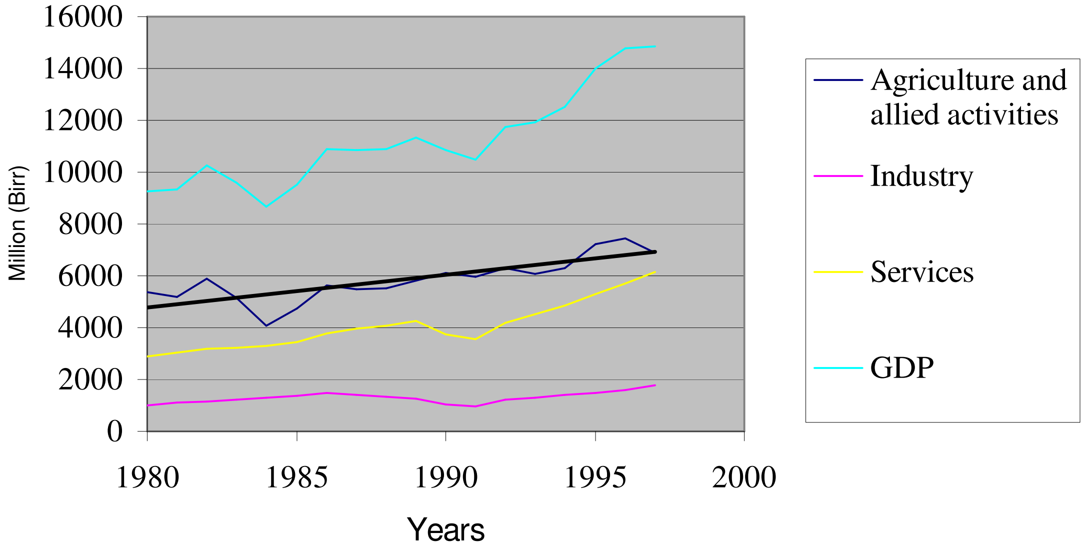

Figure 2.1. Gross Domestic Product (GDP) by sector at 1980 constant factor cost, Ethiopia, 1980-1997
Source: MEDaC (1999)

Over the years, growth in crop production by smallholder farmers has been sluggish increasing at annual average rate of 1 per cent during the 1980 to 1990 (pre-reform period) compared to 5.3 per cent in the post reform period (1991 to 1997) (Figure 2.2). These recent increases in production, however, were associated more with area expansion than yield increases. Over the last 30 years, while cereal and pulse area expanded at an average rate of 2.1per cent, cereal yields remained flat at 1.2 ton/ha (Figures 2.2 and 2.3). Area expansion has hardly been accompanied by adoption of improved farming techniques. For instance, in the years 1994 to 1998, on average, improved seeds were applied to about 2 per cent of the total area of cereals while commercial fertilizer was applied to about 38 per cent of the total area under cereals (CSA, 1999). By 1995, only

[1] State farms and producer cooperatives, which produced less than 5 per cent of the agricultural output received more than 40 per cent of the government capital expenditure budget in the 1980's.

one third of rural households used inorganic fertilizer at the rate of 11 kg per ha (Demeke et al., 1997). Among the reasons for the low productivity of agriculture, limited use of modern inputs, lack of transportation and storage facilities, inadequate extension and credit facilities, natural calamities such as drought and ecological degradation, and poor and biased agricultural policies are most prominent (Admassie and Heidhues, 1996; Demeke et al., 1997; FAO, 1999).

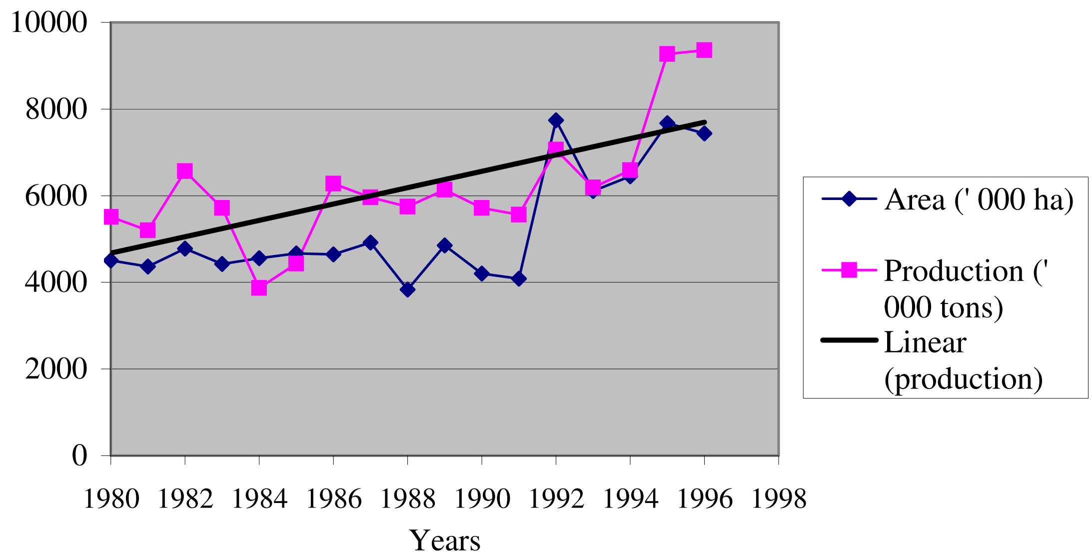

Figure 2.2. Trends in area and production of cereals in Ethiopia, 1980-1996
Source: MEDaC (1999)

At the global scale, per capita food production grew at annual rate of 0.6 per cent per annum since the 1960's (Wiebe, 1997; Shane et al., 1997). However, in SSA including Ethiopia, the last three decades have been marked by a decline in per capita food availability due to the rapid population growth relative to the growth of agricultural production (Zegeye and Habtewold, 1995; Wiebe, 1997; Shane et al., 1997; Aballu and Hassan, 1999). On the other hand, in Ethiopia for instance, population growth rate increased from about 2 per cent in the 1950's to about 2.9 per cent in the 1980's. Accordingly, the population of Ethiopia grew from 54.6 million in 1995 to 67 million in 2002 and expected to reach 120 million by 2022 (MEDaC, 1999). Consequently, per capita food production declined resulting in chronic food shortages primarily affecting the rural poor. The country with per capita income of only US $ 100 and foreign debt of more than export earnings (World Bank, 2004) lacks the means to cover domestic food production deficits through commercial imports. The deficit, however, has been largely bridged by food aid (MEDaC, 1999).

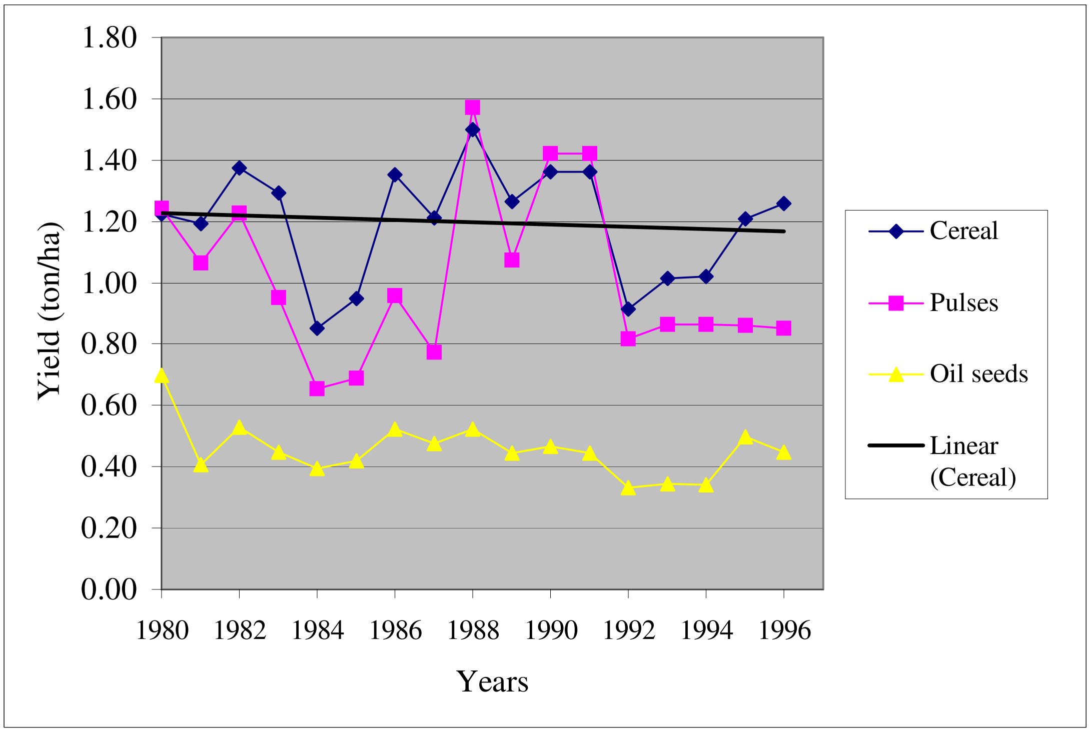

Figure 2.3. Yield trend of cereals, pulses and oil crops, Ethiopia, 1980-1996
Source: MEDaC (1999)

2.2 Overview of the soil resources and soil degradation in Ethiopia

2.2.1 Soil resources of Ethiopia

This section draws heavily on the reports of Abebe (1988) and a draft report entitled "Potentials and Research Needs for the Ethiopian Highlands" prepared by the Technical Committee for Agro-forestry (TCA) in Ethiopia submitted to the International Center for Research in Agroforestry (ICRAF) in June, 1990.

Nineteen soil types have been identified in Ethiopia, of which seven soil types namely Vertisols, Nitosols, Luvisols, Cambisols, Phaeozems, Acrisol and Lithosols make up about 88% of the soils in the highlands (Table 2.2). The importance of these soils within the highlands, however, differs from one agro-ecology to another.

In the high potential mid altitude (between 1500 and 2500 meters) zone, Nitosols and Acrisols, account for about 39.5% and 29.5 %, respectively. The relative importance of soil types is reversed in the high altitude (2,500-3,000 m) range, where Vertisols dominate followed by Luvisols.

In the low potential mid altitude (1500-2500 m) cereal zone, Cambisols and Luvisols predominate accounting for about 32% and 15%, respectively, while in the low potential high altitudes (2,500-3000 m) zone Phaeozems appear to be more important followed by Lithosols.

Vertisols are deep, black, and cracking clay soils, which expand and contract with changes in moisture content. They are low in permeability, have above average fertility and usually occur on flat to undulating topography. Their inherent texture, however, renders them less suited to many crops and often creates workability problems such as traction. In spite of their physical property, problems and their susceptibility to erosion, their nutrient retention and water-holding capacity can make them very productive (Jutzi and Mohammed-Saleem, 1992). Nitrogen and phosphorous are often the two limiting nutrients undermining the productivity of Vertisols.

Nitosols are reddish brown to red clayey soils with an accumulation of silicate clay in the B-horizon. They are dominated by kaolinitic clay and are deep with a high moisture holding capacity, physically porous, well drained and have a very good potential for agriculture. The high degree of weathering, however, induces a high capacity for P-fixation and this, coupled with the inherent low phosphorus content, makes the application of additional phosphorus a necessity for Nitosols.

Acrisols are reddish brown to red in color with argillic B-horizon and base saturation less than 50%. Physically, these soils are good because they have a well-aggregated soil structure and are porous. However, chemically they are poor due to their low pH and low available P content. They are moderately suited to agriculture and they are found associated with Dystric Nitosols.

Luvisols have distinct argillic B-horizon and a high base saturation (>50%), with varying physical characteristics such as texture, but good chemical properties. They are intensively cultivated, except in stony areas and on steep slopes, and there are permeability, workability and drainage problems in Vertic Luvisols. They have low to moderate available P content.

The characteristics of Cambisols vary because they are found under quite variable conditions. But generally, they have a B-horizon, which shows an evidence of alteration. They form under all conditions of relief (land forms); erosion and climate that are not favorable for other soil processes except weathering. These soils are predominantly found in the northern highlands.

Phaeozems have dark-colored humus-rich topsoil that contains little or no calcium carbonate. Depending on the local topography, they could be shallow, as in the northeastern escarpment, or in areas with high population density, or left for livestock grazing.

Lithosols are very shallow, young, newly weathered and weathering soils, which are extremely stony. Being less than 10 cm deep, Lithosols are too shallow for agriculture. They occur throughout the country under any one or a combination of conditions such as steep slopes, dry climate, young parent materials, or severely eroded areas.

Information on the fertility status of the Ethiopian soils is scanty. The few available evidence indicate that Potassium, Nitrogen, Cation Exchange Capacity (CEC) and organic matter contents of most Ethiopian highland soils are generally considered as high whereas their phosphorous content is low to very low (Murphy, 1963). Nevertheless, most highland soils are deficient in important nutrients and require fertilizer to sustain crop yields. For instance, Vertisols covering 10% of the geographical area of Ethiopia and about 24% of all cropped highland soils, while generally considered having above average soil fertility, nitrogen and phosphorous are the two plant growth limiting nutrients (Mamo et al., 1992). Various studies have indicated that P is a potentially limiting element for crop production in the highlands as 70 –75% of the soils of the highlands plateau region of Ethiopia are P deficient.

Table 2.2. Major types, area and distribution of soils in Ethiopia

	Dominant soil type	Area (km^2)	Area (%)	Location
1	Acrisol	55726.5	5.0	Moderate to steep slops of high rainfall areas (e.g. Western Ethiopia)
2	Andosol	13556	1.2	Northern Highlands (Western Tigray and north Gonder,), near Lake Abiyata, Lake Zway and Lake Koka
3	Arenosol	9024	0.81	On steeper slopes in the gorges of south eastern Wello at the base of Mt. Ras Dejen and in the north eastern Bale
4	Cambisol	24038	11.1	Central part of Ethiopia, north eastern escarpment, northern highlands
5	Chernozem	814	0.07	Humid temperate climate with pronounced dry seasons found on the flat pyroclastic plateau south Mt. Chilalo in Arsi
6	Fluvisols	88261.5	7.9	N.A.
7	Gleysols	5273.5	0.47	N.A.
8	Histosols	4719.5	0.42	N.A.
9	Lithosol	163185	14.7	Occur throughout the country under any one or a combination of conditions such as steep slopes, dry climate, young parent materials, or severely eroded areas
10	Luvisol	64063.5	5.8	Occur through out Ethiopia where climatic conditions are favorable for clay movement (Central Ethiopia, east and west Chercher highlands, northern highlands, parts of southern Sidamo, southern Rift Valley in the coarser textured granitic soils, further south of flood plain of Awash river)
11	Nitosols	150089.5	13.5	In the central highlands and the western lowlands, where Chercher highlands are wettest, north of Lake Tana, southern Rift Valley (moving upward out of the Rift)
12	Phaeozem	32551	2.9	Widely spread on the northeastern escarpment and northern highlands (western Tigray, northern Gonder, Wello), Central (Blue Nile Gorge) and Chercher highlands
13	Regosol	133596	12.0	Northern Wello, eastern Tigray, on sand stone plains of eastern Ogaden on flatter land forms where volcanic ash deposits are found occasionally on largely windblown slope debris materials on the flatter land forms

	Dominant soil type	Area (km^2)	Area (%)	Location
				throughout Danakil and in the eastern Danakil
14	Rendzina	16348	1.5	Moderate to steep side slope of limestone landforms in the central, northern and Chercher highlands
15	Solonchak	47217.5	4.2	Found in arid areas on colluvial slopes on evaporite deposits (Ogaden), Awash river valley, around Lake Shala, Danakil and in the extreme southern Rift Valley in the areas of Chew Bahir
16	Solonetz	495	0.04	N.A.
17	Vertisol	116785	10.5	Flat to undulating land throughout Ethiopia where fine textured colluvium collects except in the very driest areas and when the parent material is evaporite on flood plains of major rivers where fine textured alluvium has concentrated largest extents found in central Ethiopia in basins with seasonal drainage deficiencies
18	Xerosol	53171	4.8	Extensive in the semi-arid areas of Ethiopia
19	Yermosol	34950	3.1	On vast plains of the arid and semi-arid regions of Ethiopia (Ogaden) more representative for arid regions

N.A.= Information not available

Source: Adapted from Abebe (1988) and Mengistu (2003)

2.2.2 Soil degradation in the Ethiopian Highlands

Soil is a fundamental input in agriculture. Inappropriate uses of soil resources have been a concern at the global, regional and national level for the mere fact that agricultural production may not be sustainable with diminishing soil quality (Pagiola, 1999; Aballu and Hassan, 1999; FOA, 1999; Wiebe, 2003). In the Ethiopian highlands, though, all forms of soil degradation exist; excessive soil losses due to water erosion and nutrient depletion stand to be the most important (Bojo and Cassels, 1995; FAO, 1999; Elias, 2002; Zeleke, 2003).

Various authors indicated that data on land and soil degradation worldwide is extremely limited, incomplete and often unreliable (Pagiola, 1999; FOA, 1999; Wiebe, 2003). Likewise, in Ethiopia, soil degradation related data are scanty, poor in quality, mostly qualitative and at best highly location-specific posing difficulty in extrapolation of results to a wider scale (Kapple, 1996). Available data indicate that out of the 60 million hectares of agriculturally productive land, about 27 million hectares are significantly eroded, 14 million hectares are seriously eroded, and 7 million hectares are considered no more agriculturally productive (Abebe, 1990 cited in FAO, 1999).

In the highlands of Ethiopia erratic rainfall causing high surface runoff contribute to sheet and rill erosion (SCRP, 1996). Reported water erosion induced soil loss rates in the highlands varied considerably from one location to another depending on climatic conditions, soil type, land use, etc. According to FAO (1986), annual soil loss induced by soil erosion from arable lands in the Ethiopian highlands averaged 100 tons/ha with a mean productivity loss of 1.8 per cent per annum. Similarly, Hurni (1993) based on empirical studies from the Soil Conservation Research Project (SCRP) estimated the annual soil loss from croplands at 42 tons/ha. Other studies, Sutcliffe (1993) and Bojo and Cassels (1995) reported annual soil loss of 45 tons/ha and 20 tons/ha, respectively, with average productivity loss of 0.21 per cent per annum. Furthermore, losses of soil nutrients along with removed soil are staggering, about 36-429 kg/ha/year for total N, 0.412-5 kg/ha/year for available P and 1.4-17 kg/ha/year for exchangeable K (Table 2.3).

Kappel (1996) noted that this variability in estimated soil loss and its associated productivity loss rates might be attributed to the complex nature of land degradation, difficulty in measurements and uncertainty with extrapolation.

Table 2.3. Calculated range of nutrient losses removed along with water erosion induced soil loss from the highlands of Ethiopia

Plant Nutrient	Nutrient content of soil	Soil loss range (ton/ha/year)		Total amount of nutrient lost (kg/ha/year)	
		Lowest	Highest	Lowest	Highest
Organic matter (per cent)	2.0	18.0	214.4	360	4,288
Total N (per cent)	0.2	18.0	214.4	36	429
Available P (ppm)	22.9	18.0	214.4	0.412	5
Exchangeable K (per cent)	0.0078	18.0	214.4	1.40	17
Exchangeable Ca (per cent)	0.16	18.0	214.4	28.8	343
Exchangeable Mg (per cent)	0.048	18.0	214.4	8.64	103

ppm=parts per million

Source: FAO (1999)

Furthermore, Sanchez (2000) indicated that soil fertility exhaustion is the root cause of declining food production in smallholder farms of tropical Africa with fertility depletion rates 7 times larger than annual fertilizer imports. He noted that 37 African countries had lost 132 million tons of N, 15 million tons of P and 90 million tons of K from their cultivated lands during the last 30 years. In the highlands of Ethiopia, continuous mono cropping of cereals, reduced or total abandonment of fallowing, none or minimal nutrient inputs has also contributed to the negative soil nutrient balances (Tanner et al., 1992; Yirga and Hassena, 2001). For instance, wheat and barley, the two most widely grown crops in the highlands, remove 40-56 kg/ha of N, 7.8-12.3 kg/ha of P and 12.3-16.8 kg/ha of K in the grain and 16.8-33.6 kg/ha of N, 2.4-3.9 kg/ha of P and 56-67.2 kg/ha of K in its straw (Table 2.4).

Noteworthy, in Ethiopia, the high natural forests that once covered about 35-40 per cent of the country's land has largely been converted into cultivated lands. Currently, the forest cover is estimated at about 2 per cent. Obviously, the widening gap between agricultural productivity and population growth rate has resulted in major land use conflicts between arable farming, animal grazing and forestry in the highlands (Kidanu, 2003). Federal government efforts to rehabilitate degraded land, maintain and expand national parks, natural forest reserves and plantations are in sharp conflict with local people interest to clear up the areas for cultivation or grazing. Regional state and community forest interests on land enclosed for rehabilitation collide with local grazing interests. Needs of individual households for immediate grazing and fuel wood collide with community interest for woodland. The fact that there exists a conflict on land use between individual households (to expand arable farming and livestock grazing thus degrade the land) and the government (conserve land) as a custodian of public interests suggest the existence of a divergence between private and social objectives concerning the optimal level of land degradation.

Table 2.4. Mean nutrient removals (N, P, K_2O_5) of some cereals in the Eastern highlands of Alemaya, Ethiopia

Crop	Yield (kg/ha		Nutrient removals (kg/ha)		
			N	P	K
Maize	Grain	4072	100.8	17.2	28.0
	Stalk	-	78.4	12.3	106.4
Sorghum	Grain	3263	56.0	12.3	16.8
	Stalk	-	72.8	9.8	106.4
Wheat	Grain	2688	56.0	12.3	16.8
	Straw	-	33.6	3.9	56.0
Barley	Grain	2240	40.0	7.8	12.3
	Straw	-	16.8	2.4	67.2

Source: Hawando (1989) cited by Elies (2002)

Therefore, given, the expansion of cultivated lands into marginal and hillsides, continuous cropping, the high proportion of cereals in the cropping system, the use of animal manure for domestic fuel and inadequate replenishment of removed nutrients through crop harvest and organic matter, soil degradation is likely to worsen in Ethiopia.

2.2.3 Impact of soil degradation

Various studies have shown that the impacts of soil degradation have far-reaching consequences for low-income countries such as Ethiopia. Land degradation results in loss of current as well as future income, increased risk of crop failure and more importantly affects the most vulnerable group of society, the poor. While empirical research on the impact of soil degradation in the developed world emphasized off-site costs of soil degradation, studies in low-income countries focused on on-site costs that have a direct bearing on sustainability of agriculture in low-income countries reflecting the relative priorities placed on the soil degradation problem in the respective parts of the world (Barbier, 1995). In spite of the high profile placed on the problem of soil degradation in low-income countries, empirical studies estimating impact of soil degradation are few in SSA. The few studies in SSA estimated the national economic loss to be substantial, for Ethiopia ranging from 2 to 6.7 per cent of agricultural gross domestic product (Bojo and Cassels, 1995; Kappel, 1996). However, Kapple (1996) noted that available studies are severely affected by methodological problems primarily arising from the difficulty of deriving average regional or national level soil loss rates; disagreement on the net erosion rates as a result of difficulties encountered in estimating redeposition rates; lack of knowledge on land use pattern at a national or regional level; and the difficulty of establishing and quantifying definitive relationships between net soil loss and yield loss.

Other studies also estimated the opportunity cost of using livestock dung and crop residues as domestic fuel in the Ethiopian highlands in terms of lost production could be as high as 700, 000 tons of grain equivalent (Bojo and Cassels, 1995).

It is clear from the above that soil degradation in SSA in general and in Ethiopia in particular is a crucial natural resource problem affecting productivity and food security in the region. Available estimates of the impact of soil degradation are useful to the extent that they indicate the magnitude of the problem but could not provide the full costs that continued soil degradation will have on the country's economic development. Kappel (1996) noted that the few empirical studies available in SSA including Ethiopia are based on static models, which probably result in rather conservative estimates of ecological and economic damage. He further emphasized the need for studies that take into account the dynamic forces deriving soil degradation in SSA employing more rigorous approaches.

2.2.4 Soil conservation and soil fertility management efforts in Ethiopia

In response to the problem of soil degradation, considerable resources have been devoted to understand the physical processes involved in soil degradation, develop technical solutions in the form of improved technologies, adapt the technologies on farmers' fields and disseminate available technologies to smallholder farmers for widespread use. Among the most notable are the crop response trials to various levels of inorganic fertilizers (N, P, K), liming, crop rotations (Tanner et al., 1999; FAO, 1999); drainage methods to draw off excess runoff from croplands (Jutzi and Mohammed-Saleem, 1992, Erkossa et al., 1999); studies to understand the technical relationship between soil conservation methods, runoff and soil loss rate; and design soil conservation structures that stabilize and reduce soil loss (SCRP, 1996). Among the improved soil conservation practices, terraces, soil-stone bunds, check-dams and live barriers have been widely promoted by various projects and programs to control soil erosion. Inorganic fertilizers and crop rotations involving leguminous crops have also been extensively promoted to enhance soil fertility thereby reduce soil mining.

2.2.4.1 Soil conservation research and extension efforts in Ethiopia

In Ethiopia, soil conservation is as old as agriculture itself. Smallholder farmers in various parts of the highlands have been using a variety of soil conservation and soil fertility management practices with various intensities (Kruger, et al., 1996; Gebre Micheal, 1999; Regassa, 2001). However, over the years, the importance of traditional soil conservation practices except in few isolated places such as Konso in Southern Ethiopia and Ankober in North Shewa have declined owing to demographic pressures, socio-economic and institutional dynamics that took place over the last three decades.

Nonetheless, a considerable effort had been made to generate, adapt and disseminate a variety of soil conservation practices across the highlands since the 1970's. Most notable are the soil and water conservation (SWC) extension program initiated and implemented with the assistance of the World Food Program under the food-for-work project and the Soil Conservation Research Project (SCRP) initiated in 1981 in collaboration with the Institute of Geography of the University of Berne, Switzerland. The SCRP with its 7 sites[3] scattered throughout the highlands was charged with providing the necessary basic data for the proper implementation of the soil conservation program already underway; conduct basic research on soil erosion; develop soil and water conservation measures appropriate for the various agro-ecologies of the highlands; and train local personnel in this field of study (SCRP, 1996). The SCRP had developed a number of soil conservation techniques and generated a wealth of data, which has helped initiate several studies on various aspects of soil degradation in Ethiopia (SCRP, 1996; Gebre Micheal, 1999; Kapple, 1996; Shiferaw and Holden, 2001).

The achievements of the SWC program, which was implemented with the assistance of the World Food Program (WFP), were immense. Between 1980 to 1994, about 1, 045,130 ha of land were treated with soil bunds and hillside terraces, 17, 880 km check dams and cut-off drains were constructed; 1, 259, 760 ha were covered by closure and aforestation; and about 170 small earth dams were constructed (Gebre Michael, 1999).

[3] One of the sites is located in Eritrea

The achievements of the program, however, were short lived. Following the government change in 1991 and subsequent introduction of policy reforms in 1992, most of the conservation structures were either dismantled or not maintained; community forests were cut down; and enclosed hillsides for rehabilitation were opened for communal grazing (Shiferaw and Holden, 1998; Gebre Michael, 1999; Kapple, 1996; Zeleke, 2003). The most outstanding reasons often mentioned behind the failure of the intervention were:

- Top down approach which did not involve the cultivators of the land
- Over emphasis on structural measures for erosion control
- Uniform application of measures regardless of variations in agro ecological conditions and land forms
- Over dependence on food-for-work programs to carry out soil conservation structures
- Lack of a clear policy, especially concerning ownership, control and utilization of afforested areas and closed hillsides

Another major drawback of past soil conservation efforts in Ethiopia have been overemphasis of ecological effectiveness and technical simplicity as a guiding principle in the design of soil conservation practices giving little attention to profitability and economic incentives such as cost effectiveness (Kapple, 1996; Shiferaw and Holden, 2001; Okumu, et al., 2003).

2.2.4.2 Commercial fertilizer use in Ethiopia

In Ethiopia, increased use of inorganic fertilizers is considered key to reducing poverty and feeding the ever-increasing population. Consequently, a considerable effort has been placed on promoting the use of fertilizer through a combination of programmes including fertilizer trials, demonstrations and special projects.

Commercial fertilizer was introduced in Ethiopia in the 1950's with the establishment of private large commercial farms. In subsequent years, the Extension Program introduced commercial fertilizer to smallholder farmers. However, its use among smallholder farmers have become popular only after the FAO's fertilizer program known as the Freedom from Hunger Campaign (FFHC) launched in 1967. Subsequent introduction of commercial fertilizers to smallholder farmers on a large-scale basis became successful as a result of the establishment of the Minimum Package Program (MPPs) under the Extension and Project Implementation Department (EPID) of the Ministry of Agriculture (MOA) in the 1970's. The use of commercial fertilizer further became popular with the establishment of the integrated agricultural development programs popularly known as Chilalo Agricultural Development Unit (CADU) later known as the Arsi Rural Development Unit (ARDU) in the former Arsi province, the Wolayta Agricultural Development Unit (WADU) in Southern Ethiopia and the Ada District Development Program (ADDP) in the Debre Ziet area. More recently the Sasakwa 2000 Project and the Participatory Demonstration and Training Extension System (PADETES) run by MOA have also been actively involved in the dissemination of commercial fertilizers along with improved crop seeds. Thus, farmers in the highlands of Ethiopia have known and used inorganic fertilizers for over 30 years.

However, commercial fertilizer consumption in Ethiopia remained low until 1992 primarily due to supply constraints but showed remarkable increase with improved availability associated with policy reforms. Consumption increased from 190,000 ton in 1994 to 253, 000 ton in 1996 and 286, 000 ton in 1999 (Figure 2.4). For Ethiopia as a whole, the proportion of farmers using commercial fertilizers was estimated to be less than 7 per cent in 1982 (FAO, 1988); increased to 15 per cent in 1992 (Makken, 1993); and reached 31 per cent in 1997 (Demeke et al., 1997). Likewise, intensity of use measured as kg of nutrients per hectare of cultivated land grew from less than 7 kg in 1992 (Makken, 1993) to 17-20 kg in 1999 (Adunga and Demeke, 2000). Although, both the number of households and intensity of use of commercial fertilizers by smallholder farmers in Ethiopia have shown modest growth particularly after market liberalization, it still stands out as one of the lowest in Africa. The comparable figure for the year 1995 is 10 kg/ha in SSA, 65 kg/ha in Latin America, 77 kg/ha in South Asia and 216 kg/ha in East Asia (Yanggen et al., 1998).

Much worse is the low use of organic forms of fertilizer such as compost. This is mainly because much of the dung and crop residues are increasingly utilized as sources of energy for domestic use (Makken, 1993; Bojo and Cassels, 1995; Elias, 2002). Agricultural technology adoption studies conducted in various parts of the country prior to market liberalization showed that knowledge of the benefits of using fertilizer and other inputs is widespread but limited supply and late delivery of fertilizer and improved seeds hindered increased fertilizer use (Waktola, 1980; Kebede, 1990; Yirga et al., 1996; Croppenstedt and Demeke, 1996; Alene et al., 2000; Croppenstedt et al., 2003). Therefore, given the low use of inorganic fertilizers, continued use of livestock dung and crop residues as domestic fuel, high proportion of cereals in the cropping system and unabated soil erosion implies soil nutrient mining will continue to be a major challenge in the foreseeable future in the highlands of Ethiopia.

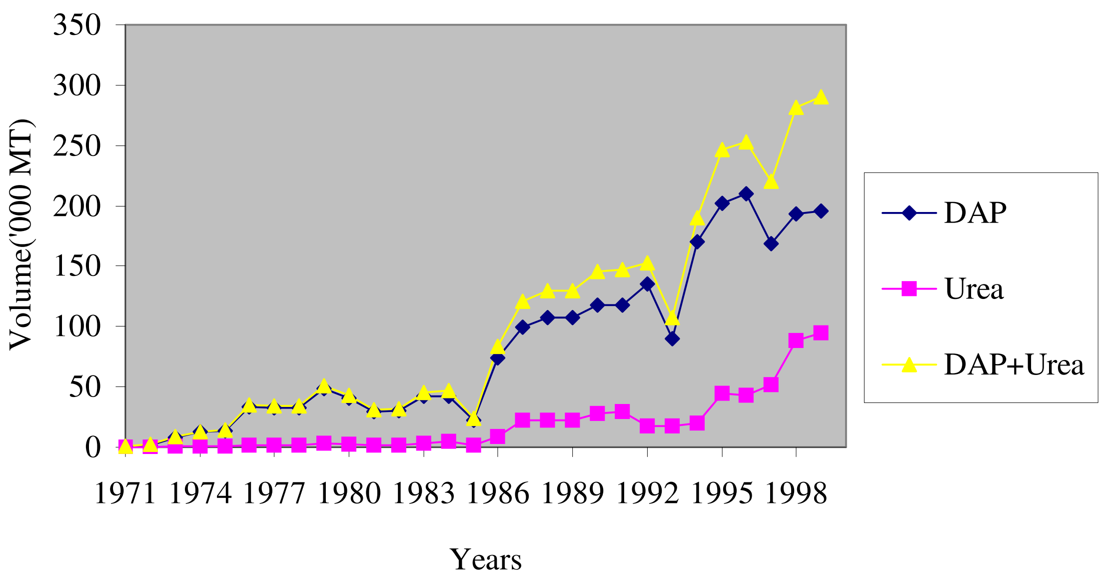

Figure 2.4. Commercial fertilizer use in Ethiopia, 1971-1999

Source: Adugna and Demeke (2000)

2.3 The policy environment

In Ethiopia, apart from the recurring drought, which has severely disrupted food production, agricultural development policies have often been blamed for the unsustainable use of natural resources (Stroud and Mekuria, 1992; Makken, 1993; Demeke et al., 1997; FAO, 1999; Adunga and Demeke, 2000). Among the economic policies of past governments that either denied enabling environment or hindered agricultural productivity include urban biased economic development policies; exploitative land tenure relationship that prevailed during the imperial government; agricultural development policies of the socialist government which were characterized by heavy control (Stroud and Mekuria, 1992; Adal, 2000; Adunga and Demeke, 2000; Haile Gabriel, 2003; Adal, 2003; Rahmato, 2004).

2.3.1 Agricultural development policy

The economic development strategies of Ethiopia in the 1970's and 1980's were largely biased against smallholder farming. The two successive Five Year Plans (1957-61 and 1962-67) emphasized industrialization and large-scale commercial farms that could produce commodities either for export or effectively substitute imports (MFD, 1957; MFD, 1962). It is only in the third Five Year Plan (1968-1973) that smallholder farming received attention. Even then, it was assumed that substantial agricultural improvements would be gained through promoting improved packages of agricultural technologies by concentrating efforts on few selected high potential areas. As a result, the vast majority of smallholder farmers producing for subsistence using traditional farming techniques on less favored areas with visible symptoms of soil degradation were neglected. Much worse, the economic development policy of the military regime which were characterized by state ownership of land, nationalization of industries, collectivizing commercial private farms, government control of agricultural input and output markets, forced food grain deliveries at fixed prices and involuntary villagization of farm households by denying favorable economic environment and the private incentives required for sustainable use of natural resources contributed to natural resource degradation (Stroud and Mekuria, 1992; Demeke et al., 1997; MEDaC, 1999; Gelan, 2002) .

The Transitional Government of Ethiopia (TGE), which replaced the socialist regime in 1991, subsequently renamed as the Federal Democratic Republic of Ethiopia (FDRE) adopted an Economic Reform Program in 1992. The economic reform program aimed at stabilization and trade liberalization to revive the economy that had suffered from many years of civil war, food security crises and heavy control (MEDaC, 1999; Gelan, 2002). The most important measures taken under this reform program include: devaluation of the local currency, disbanding of producer cooperatives, drastic reduction of subsidies to state farms, elimination of compulsory food grain quotas and liberalizing input markets (MEDaC, 1999; Gelan, 2002). These policy reforms have been further strengthened through the adoption of a new development strategy popularly known as "Agricultural Development Led Industrialization (ADLI)".

ADLI, primarily focusing on the agricultural sector, aimed at bringing about productivity improvements to the smallholder agriculture and expansion of private commercial farming. Improvements in the agricultural sector was hoped to provide commodities for exports, satisfy domestic food requirements and supply industrial inputs. Improvements in the agricultural sector in turn were expected to help expand market for domestic manufacturing as a result of increased income of smallholders. Establishing an effective input delivery and marketing system which can ensure adequate and sustained agricultural inputs such as fertilizers, improved seeds and crop protection chemicals to smallholder farmers in the required quantity, product mix, at the right time and at a reasonable price is considered key to the success of the development program (Demeke et al., 1997; MEDaC, 1999; Haile Gabriel, 2003; Bayu, 2003).

Furthermore, the current government has adopted a number of strategies and policies including a food security strategy, a poverty reduction strategy, natural resources conservation policy, resettlement policy, health policy focusing on disease prevention and a policy of free primary education aimed at reducing poverty, improve food security, develop skilled and healthy work force thereby bring a tangible improvement in the welfare of the population (Haile Gabriel, 2003; Bayu, 2003; Rahmato, 2004).

2.3.2 Land tenure regimes

Land tenure represents the social relations and institutions governing access to and ownership of land and natural resources (Maxwell and Wiebe, 1998). Land tenure through the rights and obligations it bestows on farm households thus determines both short and long-term investment decisions and the benefits landholders derive there off.

As in most parts of Africa, land tenure in Ethiopia has been the subject of debate among farmers, policy makers, researchers and the public at large. Historically, in Ethiopia, land was viewed not only as a source of livelihood to the majority of the population but also a source of political and economic power to all groups who aspire to hold political power (Adal, 2000; Adal, 2003; Rahmato, 2004). Consequently, the land tenure reforms that Ethiopia witnessed had been designed and implemented in the light of the political advantages it was presumed to yield to successive governments with very little economic rationale.

Prior to the 1974 land reform, land tenure in Ethiopia was characterized by a complex system of ownership namely communal, church ownership, private and state holdings (Rahmato, 1984; Adal, 2003). State or government holdings were most prevalent in the less densely and pastoral areas of the lowlands irrespective of geographical location. While communal ownership locally referred as “Rist” and church holdings characterized the northern highlands including Gojam, Gonder, Tigray and parts of Wollo, private holdings were a feature of the South.

The communal system (Rist) was based on the principle that land is the collective property of the community that bestows access and transfer rights to its individual members who can trace his/her kinship ties to the founding ancestors. However, land could not be sold or mortgaged. The presence of a descent system that allows an individual to be a member of different kinship groups at the same time, often arising from intermarriages, entitles the individual to claim land from several kinship groups irrespective of residence of the individual or geographical locations of the contested land. Consequently, farmers end up in endless land related litigations which claimed valuable time and resources, led to land fragmentation and in certain cases to absentee landlordism (Regassa, 2001).

In the south, private ownership of land was developed as a result of land grants by the government to loyalists of the imperial regime. As a result, land was concentrated on the hands of few individuals, which subjected the cultivators of the land to treats of arbitrary eviction and exploitative landlord-tenant relationship. Consequently, the land tenure system during the imperial regime did not provide enough incentives to the cultivators to manage land in a more sustainable manner.

Following the 1974 land reform, the government nationalized all rural land, ended all forms of tenancy, and distributed land to farm households based on family size (Stroud and Mekuria, 1992; Rahmato, 1984; Adal, 2000; Teklu and Lemi, 2004). However, farmers had only restricted usufruct rights but were not allowed to transfer their holdings in any form (inheritance, renting, share-cropping or gift). Land was re-distributed frequently in order to reduce landlessness as well as to address land quality differences until 1991. Smallholder farmers were also evicted from their holdings to give way for state farms and producer cooperatives. Various studies indicated that the land tenure policy of the military governments has resulted in diminution of size of land holdings and tenure insecurity with all its adverse effects of unsustainable utilization of natural resources (Rahmato, 1994; Adal, 2000).

Following the fall of the socialist regime in 1991, the new government introduced a series of political and economic reforms. It allowed land leasing and inheritance subject to some restrictions. Nonetheless, land remained to be the collective property of all nations, nationalities and peoples of Ethiopia under the custody of the government. The constitution entrusted regional governments to implement their own land laws. Land distribution in the Tigray region was implemented in 1990 before the rural land act was passed; in the Amhara region in 1997 and 1998 whereas other regions have not yet implemented any land distribution since the fall of the socialist government (Adal, 2000; Adal, 2003; Rahmato, 2004; Teklu and Lemi, 2004).

Essentially, the land tenure of current Ethiopia appears to be similar to what prevailed during the socialist regime. Insecure land tenure among others has continued to be one of the most important factors responsible for the slow progress of improvement in agricultural productivity and the dire condition of natural resources in the country.

2.3.3 Agricultural pricing policies

Economic theory suggests that government initiatives influence the use of agricultural inputs and consequently the relative desirability of farming practices through the provision of structures of incentives and institutional arrangements. An important policy tool pursued by governments in SSA, until recently, had been input and output price controls via parastatals which dominated the agricultural sectors from procurement to retail distribution (Franzel et al., 1992; Makken, 1993; Demeke et al., 1997; Adunga and Demeke, 2000). This has resulted in system inefficiency, limited supply attributed to shortage of hard currency and late delivery (Makken, 1993; Adunga and Demeke, 2000).

In Ethiopia, the Agricultural Input Supply Corporation (AISCO), a government parastatal, had dominated the agricultural input (fertilizer, pesticides and improved seeds) procurement and distribution until recently (Franzel et al., 1992; Makken, 1993; Adunga and Demeke, 2000). Like in most other African countries, the agricultural input market had been liberalized in Ethiopia to do away with these structural inefficiencies. The government adopted a gradual approach of: (1) easing legal restrictions on the issuing of fertilizer licences to private individuals and companies; (2) increasing the involvement of the private sector in the distribution and selling of fertilizer and agro-chemicals as well as in the production and marketing of improved crop seeds; and (3) deregulation of prices in order to establish an effective input delivery and marketing network. Farmers have also been encouraged to use improved agricultural technologies consisting of improved seeds, recommended fertilizer and weed control practices through a popular extension package since 1996. However, an important debate is currently under way among the various stakeholders (policy makers, farmer representatives, researchers and development workers) concerning the relative merits of the market liberalization as input prices has risen much more rapidly than output prices (Adunga and Demeke, 2000; Adal, 2003).

Figure 5.2 shows crop and fertilizer prices[4] for the years 1987-1997 for Ethiopia. Over the years, for which data are available, both fertilizer (DAP and Urea) and output (teff, wheat, barley and faba bean) prices have shown a steady upward movement.

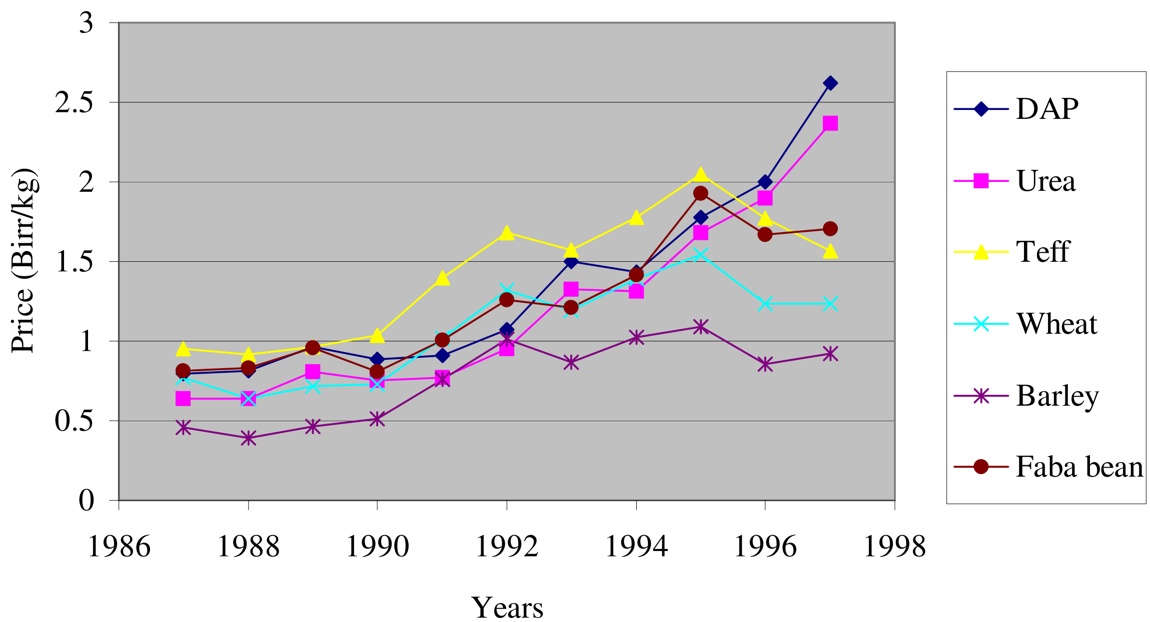

Figure 2.5. Price trends of commercial fertilizers and major crops in Ethiopia, 1987-1997
Source: MEDaC (1999), HARC (unpublished)

[4] DAP and Urea fertilizers prices pertain to wholesalers in Addis Ababa which in effect are much lower than what farmers are expected to pay at distribution points while the crop prices refer to actual prices received by farmers at a local market at Holetta some 45 km from Addis Ababa collected by Holetta Agricultural Research Center (HARC)

However, the price of fertilizer (DAP) has risen much faster than crop prices suggesting farmers terms of trade has worsened over the years (Figure 2.6)

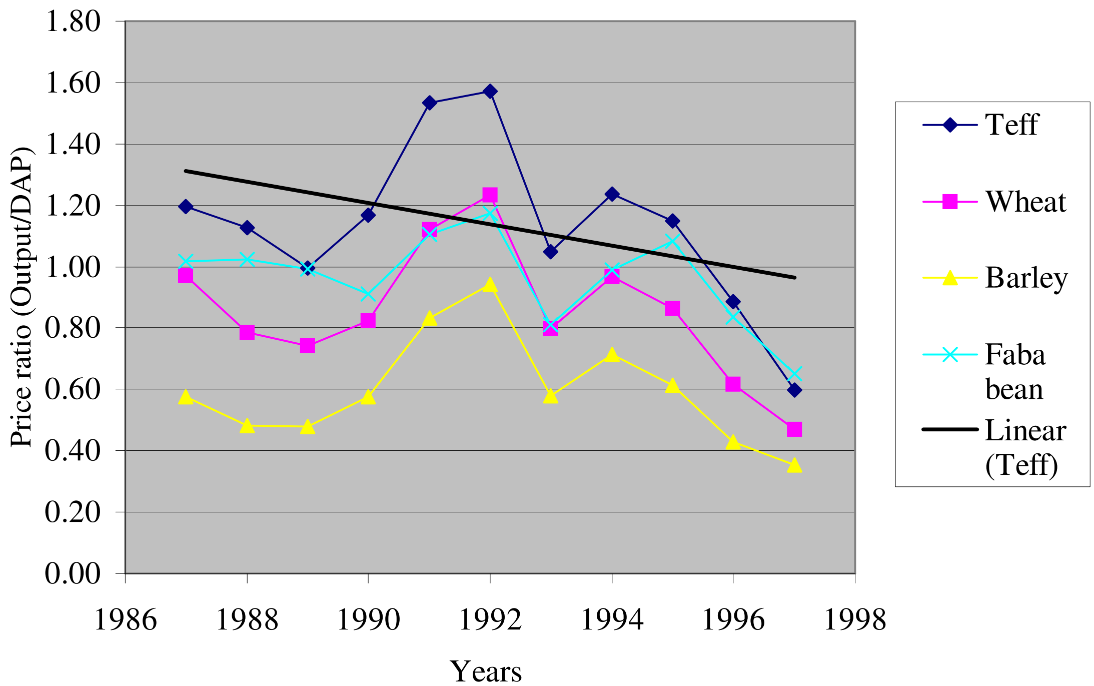

Figure 2.6. Trends in output to DAP price ratio in Ethiopia, 1987-1997
Source: MEDaC (1999), HARC (unpublished)

2.4 Summary

Over the last three decades, agricultural production and income growth in Ethiopia lagged behind population growth. Thus, per capita food production, income and savings have been falling. Disturbingly, in the highlands, soil, the basic natural resource on which the livelihood of the majority of the population is based has been progressively degraded due to a combination of biophysical, demographic and socio-economic factors. Excessive soil loss rates reaching over 100 tons/ha on croplands are not uncommon. Much worse, the amount of nutrients extracted from the soil through cropping is estimated to be several folds the nutrient inputs added to the soil in the form of organic and inorganic nutrients. As a result, crop yields have declined, at best stagnated and the number of food insecure people in the country has risen.

Past efforts to increase agricultural productivity, improve farm income, contain soil erosion and reverse soil nutrient mining have been severely hampered by inappropriate agricultural policies. Farmer incentives to invest in soil conservation and soil fertility enhancement practices have been constrained by a combination of the biophysical environment, population pressure, the institutional set up and farmer objectives. First, the institutional set-up by denying smallholder farmers secured land tenure hampered private investments in soil conservation and soil fertility enhancement. Second, the presumption that the country's food problem could be addressed through a quick fix of technological solutions prompted government and donor agencies alike to adopt a technology transfer approach focusing on short-term programs in high potential areas such as the development and transfer of improved crop technologies (improved crop varieties, commercial fertilizers, pest control measures) and public investments in simple physical soil conservation structures (soil and stone bunds) that supposedly provide quick returns at the expense of programs that have a long-term nature. Third, the high population pressure characterizing the highlands of Ethiopia led to land fragmentation as the available land have been redistributed to the increasing population over generations. Land fragmentation coupled with lack of suitable technologies to intensify farming forced farmers to either expand farming into marginal areas and/or mine the soil using traditional technologies that once were sustainable under low population pressure. Fourth, smallholder farmers primarily concerned with securing adequate food for their family immediate needs employ low-external input and erosive farming techniques which do not only mine the soil but also jeopardize the nations long-term food production ability.

CHAPTER III: REVIEW OF ANALYTICAL AND EMPIRICAL APPROCHES TO STUDYING SOIL DEGRADATION AND CONSERVATION

This chapter reviews the relevant literature on the economics of soil degradation control. The first section defines the concepts of soil capital, soil quality, soil degradation and explores the link between soil quality and soil erosion as well as soil quality and soil nutrient depletion. The section also reviews the traditional measures of soil quality and models used to estimate and predict the rate of soil erosion. Section two explores the causes for the divergence between the private and social optimal rates of soil depletion. Section three summarizes the links between soil degradation and soil productivity, which forms a prerequisite for economic analysis of soil degradation. Section four has two parts. While part one reviews the approaches often used by economists to measure and model economic costs and benefits of soil use and conservation, part two focuses on behavioral models used to analyze the adoption decision and the factors constraining smallholder farmers from adopting soil conservation and soil nutrient management practices.

3.1 The relationship between soil quality and soil degradation processes

3.1.1 The soil capital

Capital could be classified into four general categories: natural, manufactured, human and social. Natural capital is the stock of environmentally provided assets such as the atmosphere, soil, water, fish and wetlands (Sanchez et al., 1997). Soil is thus a natural capital that provides long-term economic, production and environmental service flows to society. Soil has three fundamental functions (Larson and Pierce, 1994). First, it provides the physical, chemical and biological processes indispensable for plant growth. Second, it stores, regulates and partition water flow through the environment. Third, it buffers environmental change through the assimilation of wastes. While the first function relates to agricultural production, the second and third functions relates to maintaining environmental quality through the protection of water and air quality, which in turn also affects agricultural production. The capacity of a nation's soil resources to properly function and provide a sustained flow of productive and supporting services, however, depends on maintaining and enhancing the quality of the soil capital.

Soil quality is defined as the capacity of soil to perform specific functions in relation to human needs or purposes including maintaining environmental quality and sustaining plant and animal production (Lal, 1993, 1994). Soil quality derives from a variety of particular physical, chemical, and biological properties that support these functions, including top soil depth, texture, bulk density, and water holding capacity; organic matter, pH level, and extractable nitrogen, phosphorous, and potassium; and microbial biomass. Improved soil quality can increase farm productivity, minimize the use of external inputs, improve water and air quality, and help sequester greenhouse gases (Pagiola, 1999; FOA, 1999). However, both natural processes and agricultural production can reduce soil quality and hence impair its contribution to long-term productivity and environmental quality (Lal, 1993, Lal, 1995).

3.1.2 Soil erosion and soil quality

Soil erosion is a three-step process involving detachment (or entrainment) of particles from the soil surface, down current or down wind movement of the detached particles, and deposition of the transported particles. Erosion by removing topsoil and depositing elsewhere results in a general decline in soil quality because of changes in physical, chemical and biological properties such as top soil depth, soil organic carbon content, nutrient status, soil texture and structure, water holding capacity, and water transmission characteristics that ultimately reduce crop quality and yield (Lal, 1993; Lal, 1995). On the other hand, soil mining (soil depletion or decline of soil fertility) occurs when soil nutrient extraction due to cropping exceeds soil nutrient inputs (Stoorvogel and Smaling, 1990; Ofori, 1995). Soil degradation could therefore be viewed as a decline of soil quality resulting from the twin forces of soil erosion and nutrient mining working on the physical, chemical and biological properties of soils. Lal (1988) defined soil degradation as the temporary or permanent lowering of the productive capacity of land. Soil degradation could be manifested in several forms including water erosion, wind erosion, biological degradation (decrease in humus), physical degradation (increase in bulk density, decrease in permeability), chemical degradation (acidification, toxicity) and excess of salts (salinization, alkalinization) (Lal, 1995; FOA, 1999). In SSA, soil erosion and declining soil fertility together constitute a major threat to agricultural development and sustainable natural resource management (Ofori, 1995; Brekke et al., 1999).

Natural resource capital is normally categorized as renewable and non-renewable depending on the time scale during which reproduction occurs. LaFrance (1992) considers soil as a renewable resource that is generated naturally at a slow but autonomous rate while Barbier (1995) considers it as a semi-renewable resource due to the fact that soil accretes at an extremely slow rate. Brekke et al. (1999) based on the nature of degradation suggested that when the major reason for land degradation is nutrient loss, soil resources could be safely considered as renewable natural resources since soil quality can be improved through the addition of organic and inorganic fertilizers that enables the soil resources to provide a sustained flow of services. On the other hand, if the source of degradation is from loss of topsoil and physical structures, soil resources could best be identified as slowly renewable as these damages are irreversible over a reasonable period of time. Similarly, Barbier (1995) indicated that soil in agriculture is usually treated as a potentially depletable resource due to the fact that most farming activities result in rates of erosion that exceeds the natural rate of soil erosion that would occur in the absence of cultivation practices. Knowledge of soil quality, the conditions under which it regenerates or degrades and their interaction with management is thus important in designing management practices and policies that could contribute to the sustainable use of soil resources. The two most important processes that adversely affect soil quality and hence contribute to soil degradation in Ethiopia are soil erosion and soil nutrient mining.

Various authors indicated that data on land degradation and hence soil degradation worldwide are extremely limited, incomplete and often unreliable (Lal, 1994; Lal, 1995;

Pagiola, 1999; FOA, 1999; Wiebe, 2003). Yet, available data suggest that land degradation for many countries particularly for SSA pose considerable threats to sustainability, economic growth and welfare of the people (Pagiola, 1999; FOA, 1999). A review of available figures reveals that about 11 per cent of the global vegetative land is moderately or strongly degraded (Oldman et al., 1990 cited in Pagiola, 1999). Sadly, the extent of degradation is said to be worse in Africa with 320 million ha of land moderately or strongly degraded (Pagiola, 1999; FOA, 1999).

3.1.3 Soil mining and soil quality

In SSA, soil nutrient mining or soil fertility decline is widespread and has aroused considerable concern at regional and international level (Stoorvogel and Smaling, 1990; Ofori, 1995; Sanchez et al., 1997). Stoorvogel and Smaling (1990) estimated the loss of N, P, and K from soil at 10, 2, and 8 kg/ha/year, respectively, in SSA. Similarly, Ofori (1995) indicated that at the current level of agricultural production about 80 kg/ha of nutrients is taken from soil (mainly uptake in crops removed from the land plus nutrient lost through erosion), whereas nutrient application amounts to only 12 percent (10 kg/ha) of the total. Another study by Sanchez et al. (1997) also estimated the annual nutrient losses in SSA at 4.4 million tons of N, 0.5 million tons of P, and 3 million tons of K from its cultivated land. It is therefore evident that current agricultural production in SSA is based mainly on nutrient extraction resulting in nutrient deficiency. Unlike soil erosion, however, soil mining can be relatively easily reversed through the addition of organic and inorganic fertilizers. Nonetheless, in countries such as Ethiopia, the economic impact of soil nutrient mining could be tremendous which warrants careful assessments of the tradeoffs in the use of organic fertilizers such as manure as soil amendments instead of domestic fuel.

Population growth, poverty, insecure land tenure, limited farmer knowledge of appropriate technologies, and limited access to markets, credit and risks associated with use of inputs and new technologies are often cited as the most important causes contributing to the decline of soil fertility in SSA (Reardon and Vosti, 1995; Clay et al., 1998; Shiferaw and Holden, 1998; Pender et al., 2001). Sanchez et al. (1997) indicated that among others, the break down of traditional soil nutrient management practices as a result of increasing pressures on agricultural land prompted by the need to feed increasing population in the face of shrinking land frontier is responsible for nutrient depletion in SSA. However, others argue that population pressure induces households to intensify agricultural production, invest in land improvements and develop land saving innovations eventually resulting in improved resource conditions and possibly improved welfare (Tiffen et al., 1994).

3.1.4 Measuring soil quality

Maintaining and improving the quality of soil resources has been an important policy objective both in the developing and developed world. Soil quality assessment has been an important tool for evaluating the sustainability of soil and crop management practices. However, measuring soil quality has proven to be a difficult task because it varies spatially and temporally and is affected by management and the use of soil resources (Hussain et al., 1999; Magleby, 2002; Stocking, 2003). Consequently, soil quality is viewed in two different ways (Magleby, 2002). The first and traditional view focuses on inherent soil properties and the sustainability of land for various uses such as crop production. The second view focuses on the dynamic properties of soil and the effects of soil management.

The traditional measures used to monitor soil quality and estimate the extent of cultivated land at risk of water erosion include (Magleby, 2002):

1. Land capability and sustainability. This refers to the suitability of land for a particular purpose, such as growing crops or trees, grazing animals, or nonagricultural uses.
2. Prime farmland. Based on physical and morphological soil characteristics such as depth of the water table in relation to the root zone, moisture-holding capacity, the degree of salinity, permeability, frequency of flooding, soil temperature, erodibility, and soil acidity.

3. Productivity. Measures output per unit of input. Productivity can reflect soil degradation if yields decline as soils become degraded and if input use increases to compensate for declines in soil quality.
4. Erodibility. Is a measure of the soils susceptibility to detachment and transport by the agents of erosion (Lal and Elliot, 1994). Soil texture and structure among others determines the erodibility of a given soil. Erodibility index (EI) calculated as the potential erosion divided by the soil tolerance factor have been used in the United States (US) to inventory and classify erosion potential and to determine conservation eligibility.
5. Erosion productivity loss (EPL) measures how many years it would take to remove a topsoil of a given depth at the current rate of erosion assuming all the eroded soil is removed from the field. EPL takes into account an erosion factor, soil depth, and an economic factor expressed as follows:

$$EPL = (1/\text{years of life}) * rent$$

Where, years of life refer to centimeters of sheet and rill erosion per year/centimeter of topsoil in the "A" horizon, and rent refers to the average rental rate of cropland in a specific country.

Although the above measures of soil quality are useful in determining how land might be used or the degree and location of erosion, they are limited in that they are based on physical states of soil and pertain mostly to cropland (Hussain et al., 1999). Some suggest that these traditional measures of soil quality complemented with economic measures such as cash rents and net income could provide policy makers with the minimum information needed to design and target policies for resource management. Larson and Pierce (1994) and Stocking (2003), however, argue that soil quality measures should be broad enough to reflect the various soil attributes or indicators that are controlled or influenced by the various soil functions. Consequently, measures that could better reflect the dynamic properties of soil resources such as soil quality index, soil depth, and regression equations relating various soil quality parameters and soil quality functions are suggested for use to assess soil quality (Larson and Pierce, 1994; Hussain et al., 1999). In the economics of soil conservation literature, soil depth has been used as a proxy to represent the various aspects of soil quality (McConnell, 1983; Saliba, 1985; Barbier, 1990; LaFrance, 1992).

3.1.5 Measuring and predicting the rate of erosion

Soil erosion is a process that is inherent in nature, but the rate of erosion can be drastically increased by intensified agricultural activity. Although, the detrimental effect of soil erosion is undisputable, there still exists disagreement on the extent of erosion, its effect on crop productivity, the environment and its socio-economic impacts. To this effect, modeling soil erosion, the process of mathematically describing soil particle detachment, transport, and deposition on land surface has become an important research area for soil scientists. Erosion models are valuable for the following reasons (Nearing et al., 1994):

- Erosion models can be used as predictive tools for assessing soil loss for conservation planning, project planning, soil erosion inventories, and for regulation.
- Physically based mathematical models can predict where and when erosion is occurring, thus helping the conservation planner target efforts to reduce erosion.
- Models can be used as tools for understanding erosion processes and their interactions and for setting research priorities.

Three types of models are commonly used to measure and predict the rate of erosion: conceptual, physically based and empirical (Nearing et al., 1994).

1. Conceptual Models. Conceptual models focus on predicting sediment yields, primarily using the concept of the unit of hydrology. They usually include a general description of catchment processes. These models provide qualitative and quantitative effects of land use changes. Examples of conceptual models among

others include The Agricultural Non-point Source Model (AGNPS) (Young, et al., 1989) and Agricultural Catchement Research Unit (ACRU) (Schulze, 1995).

2. Physically based models. These are primarily used to represent the essential mechanisms controlling erosion through solving fundamental physical equations describing stream flow and sediment and associated nutrient generations in a catchment. Physically based models provide information that helps to identify the parts of the system contributing to the overall erosion process. It also provides spatial and event specific information (critical seasons or months in which major erosion events occur as well as the critical positions where soil loss is highest). Examples of physically based models among others include the Water Erosion Prediction Project (WEPP), The Areal Non-Point Source Watershed Environment Response Simulation (ANSWERS) (Beasley et al, 1980), Chemical Runoff and Erosion from Agricultural Management Systems (CREAMS) (Knisel, 1980), the Erosion Productivity Impact Calculator (EPIC) (Williams et. al., 1984), the Nitrogen-Tillage-Residue Management (NTRM) (Shaffer et al. (1983); and Monitoring Nutrient Flows and Economic Performance in African Farming System (NUTMON) (De Jager, et.al., 1998).

Despite their usefulness, both conceptual and physically based models require considerable data and resources rendering them less suitable for developing countries where the database is generally insufficient.

3. Empirical Models. Empirical models, as the name suggests, are based on observation and are usually statistical in nature. The primary focus of empirical models is in predicting average soil loss. Empirical models have been widely used due to their simplicity, ease of use and low data requirement (Nearing et al., 1994). The most commonly used empirical models are the Universal Soil Loss Equation (USLE), the Revised Soil Loss Equation (RSLE) (Nearing et al., 1994; Lal and Elliot, 1994) and the Soil Loss Estimation Model for Southern Africa (SLEMSA) (Elwell and Stocking, 1982).

The USLE estimates average annual soil loss from sheet and rill erosion as a function of rainfall, soil erodibility, slope, land cover and management, and conservation practices as follows (Nearing et al., 1994; Lal and Elliot, 1994):

$$A = R * K * LS * C * P$$

Where A=estimated average annual soil loss in metric tones per hectare,

R=rainfall erosivity factor (depending on intensity, quantity, and duration),

K=the soil erodibility factor (a measure of the soils susceptibility to erosion, affected by texture and its stability, and permeability)

LS=the topographic factor (combining the effects of slope length and steepness),

C=surface-cover factor (depending on whether soil is vegetated, mulched, or bare),

P=management factor (relating the soil loss with the given management practices to the losses that would occur with up-and-down slope cultivation)

As such, the USLE is simple to use. However, being an empirical equation it could give unwarranted results if used outside the contexts for which it had been originally devised and calibrated (Nearing et al, 1994; Lal and Elliot, 1994). Since the USLE predicts the amount of soil moved on a field but not the amount removed from a field, estimates of the USLE even under the conditions for which it is designed and calibrated may overestimate the amount of soil actually lost to production (Nearing et al, 1994; Lal and Elliot, 1994). To this effect the USLE is modified to suit the peculiar contexts of countries and are widely used in many countries.

The RSLE retains the basic structure of the USLE, but the algorithms used to calculate the individual factors have been changed significantly. Estimation of the individual

factors has also been computerized (Renard et al., 1994; Rose, 1994). Like its predecessors, the RSLE over estimates soil loss for it does not consider spatial flows.
The other empirical model developed by Elwell and Stocking (1982) for Southern Africa, unlike the two earlier empirical models requires only three parameters for estimation: the rainfall energy interception of each crop, the mean soil loss on a bare fallow plot of known slope and a topographic factor for other slopes. SLEMSA is particularly appealing due to the limited information required for its estimation.

3.2 Causes of divergence between private and social rates of soil depletion

Soil conservation from a practical point of view could be considered as any practice or action taken by the land user in an attempt to reduce the effect of soil erosion by means of biological, mechanical and chemical measures. From an economic point of view, however, soil conservation implies a redistribution of resource use rates into the future, whereas depletion implies a redistribution of resources use rates towards the present (Barbier, 1995). This essentially implies like any other investment decisions, farmers, intending to invest in soil conservation are faced with inter-temporal resource allocation decisions and hence have to consider not only current costs and benefits but also future costs and benefits associated with the investments. In developing countries including Ethiopia, the rate of soil depletion from a social point of view is believed to be excessive and is a cause for concern (Bojo, 1992; Bishop 1995; Barbier, 1995; Eaton, 1996). The divergence between the optimal private rate of soil erosion and the social rate arises from:

1. Externalities. An externality occurs whenever the activities of one economic agent affect the activities of another agent in ways that are not reflected in market transactions. Externalities are thus costs and benefits arising in the process of production and consumption, which are not reflected in market prices. Example of negative externalities arising from soil erosion includes sedimentation of dams and irrigation channels. While society as a group is concerned with both on-site

and off-site effects of soil erosion, individual farmers are primarily concerned with on-site effects. Farm households as rational economic agents equating their private marginal costs and benefits of soil conservation, which do not include off-site externality costs and hence are likely to under invest in soil conservation due to the divergence between private and social objectives concerning the optimal soil conservation level (Barbier, 1995, Bishop, 1995; Shiferaw and Holden, 1999). Consequently, in a setting where there exist significant off-site costs, the optimal private and social rates of soil erosion diverge considerably.

2. Imperfect land and capital markets. Under perfectly competitive conditions prices reflect the marginal scarcity value of using resources. However in most less developed countries, markets for agricultural input and outputs are far from competitive and even totally absent for some assets such as soil quality (Barbier, 1995, Bishop, 1995; Shiferaw and Holden, 1999). For instance, in the highlands of Ethiopia, farmers have only usufruct rights to land, but land is neither traded nor used as a collateral. Consequently, smallholder farmers may not take the full user costs of soil erosion into consideration when making decisions regarding soil conservation investments resulting in too little conservation than society desires. The same applies to capital markets operating in such settings where farmers usually face major imperfections that often raise the opportunity cost of using available funds for making long-term investments in soil conservation. Hence, smallholder farmers facing imperfect capital markets and who often lack access to risk mitigation mechanisms if left on their own may under invest in long term soil conservation structures.

3. Time preferences. Time preference refers to the value people attach to present against future income (Barbier, 1995). Time preference is commonly considered to have two components, pure time preference and the marginal opportunity cost of capital. While pure time preference refers to the people's attitude to risk and uncertainty as well as to household poverty, the marginal opportunity cost of capital represents the scarcity value of savings and returns to alternative

investments. The discount rate, representing both pure time preference and the marginal opportunity cost of capital, is often used to compare present and future costs and benefits arising from alternative investments (Barbier, 1995; Bishop, 1995). The discount rate employed by private individual farmers in general and smallholder farmers in SSA in particular are considered to be very high compared to what society as a group deems appropriate suggesting individual farmers attach less value to the future and hence degrade the environment much faster than society as a group wishes (Barbier, 1995; Bishop, 1995). For instance, Shiferaw and Holden (1999) in the Ethiopian highlands estimated the nominal discrete rates of time preference among smallholder farmers to be 71 per cent on average. The high time preference displayed by smallholder farmers is believed to be associated with poverty, risk aversion behavior and insecure land tenure. On the contrary, society as a whole having a wider asset base is less risk averse and thus displays lower time preferences. Hence, the optimal rate of soil depletion for society would be much lower than the level chosen by individual farmers (Barbier, 1995; Bishop, 1995).

4. Technological improvements. Obviously, technological innovations are geared either to devise substitutes or increase the productivity of scarce resources (Bishop, 1995). In the short run, technological innovations by increasing the productivity of soil resources (e.g. through the use of improved seeds) or providing substitutes for lost nutrients (e.g. commercial fertilizer) might reduce the economic significance of soil degradation both in the developed and developing countries. However, in the long run, the soil capital being an essential input in agriculture particularly in developing countries where chances for a technological break through is slim, soil degradation will continue to be a potential threat to sustainable agricultural development.

5. Policy incentives. Government intervention in agricultural markets in SSA is widespread and believed to have significant effects on farm level incentives for conservation (Makken, 1993; Barrett, 1991; Adugna and Demeke, 2000). Policy

distortions arising from interventions in input and output markets, exchange rate manipulations, insecure land tenure and imperfect competition often distort the true costs and benefits of soil conservation thereby affect farmer perceptions about the optimal level of soil conservation (Barbier, 1995; Gelan, 2002). Recently, governments in SSA have begun implementing structural adjustment programs to do away with the structural inefficiencies associated with market interventions. However, the effect of such programs on the environment is still debated (Bulte and Soest, 1999). Barbier and Burgess (1992) and Barbier (1995) pointed out that agricultural pricing policies could affect farmer incentives to invest in soil conservation practices in the following ways:

- Higher aggregate crop prices and lower agricultural input costs increase the profitability of crop production, thus encouraging an aggregate expansion of agricultural production onto marginal or more erodible land.
- Changes in the relative prices of crops (and crop inputs) can influence the substitution of more environmentally benign cropping and farm production systems for systems that are more environmentally damaging.
- The variability of crop price inputs can affect farmer's choice of crops and cultivation practices, and decisions to invest in sustainable land management, by affecting the risks associated with alternative agricultural investments and production systems.

A number of studies have attempted to predict the effect of an increase in either input or output price on farmer incentives for soil conservation (Barrett, 1991; Clarke, 1992; LaFrance, 1992; Bulte and Soest, 1999). However, the results are inconclusive[5]. Therefore, attempts to redress policy distortions to bring about the private rate of soil depletion in line with the optimal social rate of soil depletion need improved understanding of the biophysical and economic processes involved in land degradation (land quality and agricultural production) and the decision-making behavior of farmers shaping that relationship (Pagiola, 1999; Wiebe, 2003).

[5] Detailed discussions on models and results are provided in section 3.4.1

3.3 Effect of soil degradation on agricultural productivity

As has been indicated in section one of this chapter water erosion adversely affecting soil quality is the most important contributor to soil degradation. Lower soil quality in turn impairs the capacity of soil resources to perform its multiple functions imposing on-site costs to individual farmers and off-site costs to society. On-site effects are those that happen at the site where soil degradation occurs whereas off-site effects are those that happen outside the confines of the farm boundary. While the principal on-site economic impact of soil loss is yield reductions, off-site effects of soil erosion include siltation of irrigation systems, crop failure at low laying areas due to flooding, diminished storage capacity and damage to physical plant in hydroelectric power generation schemes, and water quality deterioration affecting drinking water supplies and the productivity of inland and coastal fisheries (Bishop, 1995; Barbier, 1995). Individual farmers, however, are concerned with the effects of soil degradation on the productivity and hence income on their own farms (on-site costs).

Evidence on the forms, rate and extent of erosion are ample (Lal, 1994; Pierce and Lal, 1994). Also, the detrimental effect of erosion on agricultural productivity is not disputed. However, there is still lack of quantitative data on erosion's impact on productivity. Lal (1994) and Pierce and Lal (1994) noted that the difficulty of understanding, and establishing definitive relationship between fall in soil productivity and erosion has been clouded by a multitude of factors:

1. The magnitude of effect of soil erosion on crop productivity is conditioned by location specific attributes such as soil type, topography, soil management system, and microclimate and crop type. The location specificity of results thus limits extrapolation of results to wider areas.
2. Even if it is possible to collect and assemble location specific data from many locations and over time, the difficulty of partitioning (singling out) the contribution of soil erosion to yield decline out of a multitude of factors such as precipitation poses further problem.

3. The interplay of many of the factors affecting crop yield are also poorly understood.

Nonetheless, great strides have been made to understand the relationship between productivity and soil erosion. Summary of the traditional research approaches used to evaluate erosion's impact on crop productivity and the general conclusions drawn from 50 years of erosion and productivity research in the United States (US) are compiled and provided by Pierce and Lal (1994).

Stocking (1984) noted that much of the erosion-productivity studies have been conducted in the temperate regions. Reviewing the studies in both temperate and tropical regions, Stocking (1984) indicated that absolute yield declines due to erosion appear to be much greater in the tropics than the temperate regions. He further indicated that yield declines in the tropics are worrisome, as initial yields tend to be lower in the tropics than in the temperate regions. A recent review of plot level studies by Stocking and Tengberg (1999) in various parts of the developing world indicated that crop yields generally decline in a negative exponential or logarithmic form with soil erosion, but that both erosion rates and yield impacts vary widely with soil, slope, cover, and other site specific properties. Similarly, a review of costs of land degradation studies by Bojo (1996) showed that productivity losses in SSA varied across countries but generally considered as modest, standing at about 1 per cent or less. Wiebe (2003) reviewing the impact of land degradation on soil productivity showed that the studies so far conducted at regional and global scale suggest that land degradation to date had significant impact on productivity or quality of cropland in some areas, but not others. He further noted that impacts are sensitive to location specific biophysical and economic factors and thus remain unclear at regional and global scales.

3.4 Approaches to measuring effect of soil degradation on income and adoption decision behavior of smallholder farmers

Research on the economics of soil erosion and conservation can broadly be categorized into two categories (Eaton, 1996; Bekele, 2003). The first category of research deals with the application of formal economic models aimed at estimating the costs and benefits of soil conservation and consequently identifies tradeoffs against or in favor of soil conservation. The major contributions of the approach have been in quantifying the benefits of soil conservation thereby providing economic justifications and singling out the impact of specific factors such as prices and the discount rate on land management decisions of a profit-maximizing farmer (Eaton, 1996; Grepurend, 1997a; Bekele, 2003). The second category of research concerned with the behavioral issues is aimed at identifying and quantifying the determinants of factors constraining adoption of soil conservation practices among land users.

3.4.1 Approaches to measuring economic costs of soil degradation

Modeling approaches to the economic analysis of soil degradation and conservation could be categorized as those using normative models and those using positive models (Caswell et al., 2001). Normative modeling approaches based on the principle of optimization posit to estimate the effects of policies that limit input use or the use of certain production management practices. Positive modeling approaches to the analysis of soil degradation control, on the other hand, use econometric methods that involve the estimation of the production technology parameters from observed input and output values. Positive modeling approaches are also used to identify factors that actually affect adoption and assess the importance of those factors on adoption decisions (Caswell et al., 2001).

3.4.1.1 Positive modeling approaches to measuring economic costs of soil degradation

The most widely utilized positive models to estimate and model soil degradation control includes: productivity loss, replacement cost, hedonic pricing and net benefit of conservation. Besides, these models are static in that they are useful to examine equilibrium situations at a point in time.

3.4.1.1.1 Productivity loss approach

The productivity loss approach measures farm revenue foregone due to erosion induced topsoil reductions (Bishop, 1995; Barbier, 1995; Bojo, 1996). The accuracy of this approach is basically as good as the yield estimates resulting from erosion. Bojo (1996) indicated that crop productivity losses due to land degradation could be measured using five different but related methods: expert judgment, inferred soil loss-yield decline functions, directly estimated soil loss-yield decline functions, soil depth loss-yield decline functions and plant growth models. These methods provide critical information on erosion rates and crop yield estimates used to derive functional relationships between topsoil loss and crop productivity. The yield losses are then valued at some assumed future crop prices. Bishop (1995) noted that poorly defined relationships between crop (or livestock) yield and land degradation often limit widespread application and accuracy of this approach. Examples of studies using this approach include works by Bishop and Allen (1989) in Mali and Magrath and Arens (1989) in Java, Indonesia.

3.4.1.1.2 Replacement cost approach

The replacement cost approach measures the on-site economic costs of soil degradation through estimating the costs of additional inputs required for compensating lost nutrients (Barbier, 1995; Bishop, 1995; Bojo, 1996). The logic behind this type of study is to calculate the loss of nutrients (e.g., N, P, and K) and put a value on it by using the equivalent cost of commercial fertilizer. Generally the analysis proceeds in four steps (Barbier, 1995; Bojo, 1996). First, the mean rate of soil loss per hectare is estimated for sample areas of different types of cropland using empirical erosion models such as USLE, RSLE and SLEMSA. Second, the associated nutrient losses are estimated using regressions. Third, the costs of replacing the nutrient losses per hectare are valued in terms of nominal and shadow prices using the cost of the commercial fertilizer replacement. Fourth, the national level area subject to erosion is estimated to derive the gross losses in national income caused by erosion.

The major limitations of the replacement cost approach (Barbier, 1995; Bishop, 1995; Bojo, 1996) include:

- It may over-state on-site costs since it is based on replacing the entire mineral stock, whilst the rate at which nutrients become available for crop growth and the low actual uptake of minerals means that fertility may be maintained without complete replenishment.
- This approach does not take into account the thresh-hold beyond which the effects of erosion are irreversible.
- It is also argued that soil erosion affect several yield determining parameters apart from nutrient losses.

Nevertheless, Bojo (1996) suggested that the replacement cost approach is simple to apply when nutrient loss data are already available. He stressed the need to adjust for availability of lost nutrients to plants. Even then, nutrient loss cost is only a proxy for the actual productivity loss, which could be more or less than the cost of nutrient loss.

As noted above, estimates of the cost of degradation are often based on the value of production foregone or the cost of restoring the land, relative to a benchmark in both cases. A major weakness often cited against both the productivity loss and replacement cost approach is their failure to measure the marginal value of soil quality.

3.4.1.1.3 Hedonic pricing

Hedonic pricing also referred to as the land market approach presupposes that the rental or sale price of land appropriately reflects soil quality differences in a setting where there exists a perfectly functioning market (Bishop, 1995). The approach presents the most direct reflection of a reduction in the discounted present value of the income generating potential of a particular plot of land, relative to alternative investments. The applicability of this approach, however, is limited in most developing countries where land markets hardly exist, property rights are not well defined and land related data are unavailable.

3.4.1.1.4 Net benefit of conservation

Another approach often used to measure on-site costs of land degradation is the net benefit of conservation derived from soil conservation based yield differentials relative to yields on similar control plots without conservation (Bojo, 1992; Bishop, 1995). This approach is basically a conventional cost-benefit analysis (CBA) of returns with and without soil conservation appropriately discounted and compared using appropriate evaluation criteria most often the net present value. Bojo (1992) reviewing 20 studies applied CBA analysis pointed out the following limitations: 1) monetary measures are unethical, 2) overemphasizes the quantifiable, 3) aggregation value over individuals serves to hide conflicts, 4) a problem of the price to be used, 5) results can be manipulated to cover vested interests, and 6) incorrectly assumes rational use of economic results for decision making

Despite these limitations, Bojo (1992) suggested that cautious use of CBA is still beneficial for decision making for soil conservation projects.

3.4.1.2 Normative modeling approaches to measuring economic costs of soil degradation

Most commonly utilized normative models to estimate and model soil degradation control includes: linear programming (LP), dynamic programming and optimal control models. While LP could be formulated both in static and dynamic frameworks, the other two are strictly dynamic. A static optimization model does not consider the dynamics between farmers' decisions to use conservation practices, soil degradation and crop yields. Static decision models are appropriate if current actions do not affect future choices. For example if future nutrient stocks are independent of current levels of crop production practices and soil conservation investments, then static farming strategies are optimal. However, static strategies lead to sub-optimal outcomes if future soil nutrient stocks depend on current erosion levels, farming intensities and levels of soil conservation investment. In contrast, dynamic optimization models consider the inter-temporal interactions between these factors and soil quality attributes (Chiang, 1992; Léonard and Long, 1992).

3.4.1.2.1 Static linear programming models

The static LP modeling approach to soil degradation control analysis uses an optimization framework that links economic factors with biophysical conditions of the soil at a point in time. In these models, optimal solutions are obtained assuming some objective criteria of the decision-maker such as profit maximization subject to various constraints such as technology, resource conditions as well as other household specific conditions (Miranowiski, 1984; Cárcamo et al., 1994). Two limitations of static LP optimization models often raised in the literature are that static LP models are deterministic in that they do not provide for the stochastic nature of the erosion process and its influence on farm income patterns over time. Further more, they are highly simplified versions of real world systems with many computational restrictions.

3.4.1.2.2 Dynamic optimization modeling approaches

As has been indicated in section one of this chapter soil quality is dynamic and continuously subjected to both natural and human induced factors (cultivation and conservation) of degradation and regeneration. Intensified agricultural activities in particular entail a certain level of soil loss over and above would have occurred under natural conditions. This essentially implies current level of agricultural activities affects the stock or quality of soil available for future use. Hence, the effect of reduced soil stock or quality on crop productivity and income is dynamic in that current levels of soil loss or reduction in soil quality affect not only current levels of agricultural productivity but also future productivity and income.

Dynamic optimization models, unlike static optimization models which provide a single optimal magnitude for every choice variable considered, trace an optimal time path for each choice variable in a given time interval (Chiang, 1992; Léonard and Long, 1992). It also provides opportunity to integrate economic variables with biophysical processes and hence allow incorporating feedback effects of economic factors on management decisions. Dynamic optimization models are thus suitable for modeling the inter-temporal effects of soil degradation and conservation for both soil degradation and conservation are dynamic in nature (Burt, 1981; McConnel, 1983; Grepperud, 1997a; Brekke et al., 1999; Kruseman and Bade, 1998; Barbier and Bergeron, 1999; Ruben and Kuyvenoven, 1998). The three widely utilized dynamic optimization models often employed in modeling soil conservation are dynamic LP, dynamic programming and optimal control models.

3.4.1.2.2.1 Inter-temporal linear programming models

Owing to the limitations of the static LP models, a dynamic formulation of LP models with an explicit incorporation of the time dimension have become popular for decision support purposes to simulate the effect of socio-economic factors such as population pressure, market pressures, and agricultural policies on soil degradation, crop productivity and farm income at farm, village or regional level (Ruben and Kuyvenoven, 1998; Kruseman and Bade, 1998; Barbier, 1998; Barbier and Bergeron, 1999). Ruben and Kuyvenoven (1998) indicated that LP models combined with biophysical models, often referred to as bio-economic models, integrating technological and behavioral elements are useful in resource depletion studies and help identify the right incentives that could enhance farmers' adoption of more sustainable cropping practices.

Among the noteworthy empirical studies, which applied dynamic LP models, include Kruseman and Bade (1998), Barbier (1998), Barbier and Bergeron (1999), Shiferaw and Holden (1999) and Shiferaw and Holden (2000).

Barbier (1998) used an approach combining a dynamic LP model of economic behavior with a biophysical model of plant growth and the condition of the soil to simulate a village's response to population and market pressure. Likewise, Barbier and Bergeron (1999) developed a bio-economic model combining dynamic LP with a biophysical model and applied it at a watershed level to investigate intensive vegetable pathway of development and generate possible policy actions for similar contexts.

Shiferaw and Holden (2000) used a non-separable farm household model based on a dynamic LP to investigate the role of alternative policy instruments for soil conserving land. This model was used to identify a production plan which maximizes annual net return defined as current net returns less the present value of future income loss caused by land productivity decline due to soil erosion subject to various farm level resource supply and behavioral constraints. In another study, Shiferaw and Holden (2001) applied whole farm LP model to identify a production plan that maximized annual income defined as current net returns (on-farm and off-farm) less the present value of future income loss caused by yield losses resulting from soil erosion subject to various farm level resource supply and behavioral constraints.

The major limitation inherent in optimization models including dynamic LP is the absence of a detailed specification of the decision making procedures at the producers level, the neglect of other objectives than profit maximization, and the assumption of perfect markets. Besides resource allocation is strictly based on best technical means (Ruben and Kuyvenoven, 1998).

3.4.1.2.2.2 Dynamic programming models

A dynamic programming model is based on Bellman's principle of optimality, which states, an optimal policy has the property that whatever the initial state and decision are, the remaining (abridged sequence) must still be optimal in its own right- as an optimal path from its own initial point to the terminal point (Chiang, 1992; Léonard and Long, 1992). Dynamic programming formulation of a natural resource use problem consists of two features (Chiang, 1992; Léonard and Long, 1992):

- It embeds the given control problem in a family of control problems, with the consequence in solving the given problem, the entire family of control problems are solved.
- For each member of this family of problems, primary attention is focused on the optimal value of a functional rather than on the properties of the optimal state path as in the calculus of variation or the optimal control theory.

Application of dynamic programming models in empirical analysis of the economics of soil conservation, however, is limited due to the fact that the solution of continuous-time problems of dynamic programming involves the use of partial differential equations. Besides, partial differential equations often do not yield analytical solutions (Chiang, 1992; Léonard and Long, 1992).

Nonetheless, Burt (1981) analyzed the optimal level of crop rotation and rate of organic matter using a dynamic programming framework in the US. Burt (1981) assuming farmers maximize the present value of net returns over an infinite time horizon modeled the inter-temporal choice of soil conservation practices using two state variables (topsoil depth and percentage of organic matter in the top six inches of soil) and one control variable (crop rotation-percentage of wheat area). Using data from the 1950's and empirically solving the model, Burt (1981) showed that at higher wheat prices 87.5 per cent of the rotation would be in wheat for almost the entire domain of the two state variables. When a lower price is assumed, however, the percent of land under wheat decreased as percentage of organic matter decreased. He concluded that higher grain prices worsen soil erosion problems. Burt's model, however, was criticized for the way the control variable (percentage of wheat area) was specified as it unambiguously implies higher prices induce more soil loss. The model was also criticized for failing to consider conservation practices explicitly.

Another study that utilized dynamic programming optimization modeling approach is that of Hopkins et al. (2001) in the US. Recognizing that both nutrient mining and soil erosion as important sources of soil degradation, the authors investigated the likely economic implications of productivity losses from both irreversible physical topsoil degradation and reversible nutrient mining. In this model, level of fertilizer input and residue management are control variables whereas topsoil depth and the condition of soil nutrients are state variables. Assuming that producers maximize the expected present value of net returns from corn production, the model chooses the optimal levels of fertilizer and residue management given that the dynamics of the state variables, soil depth and condition of soil nutrients jointly determine corn yield. Hopkins et al. (2001) applying their model to nine soil types of the US drew the following conclusions. First, given soils with different characteristics such as initial properties, susceptibility to degradation, differential yield responses to management and etc., dynamic optimal economic strategies could not be inferred from physical responses but can be inferred from associated economic implications. Second, optimal residue management responds more to nutrient management than erosion. Third, substantial gains are possible from nutrient management than reducing topsoil loss due to erosion.

3.4.1.2.2.3 Optimal control models

Optimal control models are based on the mathematical programming techniques of microeconomics with a time dimension. A typical optimal control formulation consists of two features. First, it should consist of three types of variables namely: state, control and time. Second, optimal control theory has as its primary aim the determination of the optimal time path for a control variable (Chiang, 1992; Léonard and Long, 1992). The optimal control formulation of dynamic optimization problems is therefore preferred for modeling soil degradation as it enables direct determination of the optimal time path of control variables, a management/policy instrument that enables one to influence the state variable(s).

Among the noteworthy theoretical and empirical studies, which applied optimal control models include McConnell (1983), Saliba (1985), Barbier (1990), Barret (1991), LaFrance (1992), Clarke (1992), Grepperud (1997b), Goetz (1997), Brekke et al. (1999) and Nakhumwa (2004). The works of McConnell (1983) laid the foundation for the application of optimal control theory to the analysis of the economics of soil degradation control. Latter works, basically, are either modifications or extensions of McConnell's (1983) model. A brief review of the most influential optimal control models in the soil conservation literature are given below.

In his optimal control model, McConnell (1983) assumed farmers maximize the present value of the stream of net profit plus the market value of their farm at the end of the planning horizon. This formulation clearly indicates that the returns to the farm from the use of soil has two components: the value of soil as an input to agricultural production over time contributing to profits and the stock of the soil resources at the end of the planning period affecting the resale value of the farmer's land. McConnell specified agricultural inputs and soil loss as the decision (control) variables and soil depth as a state variable. Crop yields were modeled as a function of soil depth, soil loss, and input use and further assumed to be concave and twice differentiable. Crop yields increase with soil loss, soil depth and input use with diminishing returns to crop production associated with each of these variables. The equation of motion, change in soil depth, was specified as the difference between the natural rate of regeneration and soil loss. McConnell (1983) analytical results provided the optimality conditions for a profit-maximizing farmer:

- Private individual farmers use variable inputs until the value of its marginal product equals their cost.
- Soil loss will be incurred until the value of returns obtained from additional soil loss equals the implicit cost of using the soil. The cost of soil loss in foregone

future profits is the change in the productivity and sale value of the farm caused by having less soil.

- The implicit cost of soil loss should grow at the rate of discount less the soil's contribution to current profits.

The implication of the above first order conditions is that any change which would increase the costs of soil loss or decrease the benefits would lead to a reduction in soil loss and vise-versa (Eaton, 1996). Further performing comparative analysis for three alternative tenure arrangements (owned family farms, rented family farms and corporate farms), McConnell (1983) concluded that the private rate of soil depletion converges to the socially efficient level under efficient capital markets. Eaton (1996), however, argued that McConnell's conclusions might not be applicable to most developing country settings characterized by pervasive market imperfections or even missing markets. Furthermore, McConnell's model is criticized for ignoring conservation efforts as a decision variable and inclusion of soil loss as a control variable (Saliba, 1985). The use of soil loss as a control variable is considered unrealistic in a farm level model as farmers do not choose soil loss directly but do so by choosing suitable management practices such as crop rotation and other soil conservation practices. Despite the limitations and criticisms leveled against McConnell's model, it remained vital in pointing out how farmers react to changes in discount rates and for further setting out the direction for future research (Saliba, 1985; Eaton, 1996).

Saliba (1985) acknowledging the contributions made by preceding soil conservation models argued that earlier models had at least three limitations: failure to explicitly specify conservation efforts, inadequate specification of erosion-soil productivity linkage, and lack or inadequate specification of cropping intensity. Saliba (1985) further suggested that a complete farm level soil conservation model should include the following variables and functions:

- Functional relationships which capture the impact of farm management choice (the control variable) on soil attributes (the state variable);

- State variables reflecting changes in soil depth and other productivity related soil characteristics;
- Erosion-productivity linkages relating changes in soil characteristics to crop yields; and
- Crop yield functions incorporating both soil productivity and management variables that would allow substitution possibilities between soil and other inputs.

Accordingly, the optimal control model developed by Saliba (1985) included three decision variables namely, conservation effort, an index of management intensity and crop intensity and one state variable, soil depth. Like its predecessors, Saliba's (1985) model posits that farmers maximize the present value of the stream of net revenues from their farms plus the market value of the land at the end of the planning horizon by choosing crop rotations, level of management intensity and soil conservation effort. Though, Saliba (1985) provided the first order necessary conditions for optimality, the author did not numerically solve the model.

Barbier (1990) extending McConnell's (1983) optimal control model by including a soil conservation variable as a control variable showed that farmers will invest in soil conservation up to the point where the marginal cost of investing in soil conservation equals the marginal benefit. The model also pointed out that an increase in the discount rate lowers farmers incentives to use soil conservation practice thus result in greater soil erosion.

Later models, Barrett (1991), Clarke (1992) and LaFrance (1992) all emphasized the role of price incentives in soil conservation decisions but their models differ in the treatment of soil conservation inputs as a decision variable and the specification of erosion (soil loss) functions.

LaFrance (1992) considered the case where cultivation increases the rate of crop production but degrades the soil whereas conservation reduces the rate of crop production and increases the rate of soil growth. LaFrance further assumed that the erosion function is independent of soil depth (stock). The objective of the rational farmer was assumed to be maximization of the discounted net present value of the commodity prices from crop production. LaFrance's results showed that the impact of price change on rate of soil degradation depends on the relative strength of cultivation over conservation. If the effects of cultivation dominate the effects of conservation in the soil dynamics, an increase in the price of the crop accelerates the rate of soil degradation in the short run and decreases the long-run stock of the soil resources. On the other hand, if the effects of conservation dominate the effects of cultivation, an increase in the price of the crop decelerates the rate of soil degradation in the short-run and increases the long-run stock of the soil resources.

Clarke (1992) focused on soil-conserving investments, which do not affect crop yields directly. He further assumed that soil quality is depleted in proportion to the current intensity of production as measured by output implying the magnitude of soil loss increases with soil depth. The farmer is assumed to maximize the discounted value of profits over an infinite time by selecting time paths for investment in soil quality and the variable input. Clarke (1992) claimed that the effect of output price change depends not only on current profits but also on the existence of viable soil conservation technologies as well as the complementarity/substitutability of inputs and hence effects of output price change may go either way. He showed that in a setting where viable conservation technologies are available and where the use of variable inputs and conservation investments are complementary, favorable input and output price movements result in the intensive use of more of each input and lower equilibrium level of soil degradation. On the other hand, if inputs are substitutes even in a setting where there are viable soil conservation technologies, soil quality may decline.

Barrette (1991) considered soil depth as a state variable and soil loss due to cultivation as a decision variable. Barrett (1991) results demonstrated that agricultural price reforms would have only modest effects on soil conservation.

Grepperud (1997a) indicated that a common feature of earlier models, those explicitly considered soil conservation as a control variable, is that conservation efforts are assumed to be effective only in the time period they are implemented. However, although some conservation practices may have time limited effects (must be implemented every year to have a beneficial effect) others such as terraces, stone and earth bunds could be viewed as investments in land having an anticipated life beyond the current period. To this effect, Grepperud (1997a) extending LaFrance's (1992) model introduced soil conservation investment as having a lasting impact beyond the time they are implemented as a decision variable. As in LaFrance's model, this model assumes that productive inputs degrade the soil whereas larger stock of conservation structures lower soil and fertility losses. While the results of this model (investment model) are similar to earlier models, the investment model differs in that conservation inputs are employed until their marginal cost equals their marginal benefit where marginal benefit is defined as the gain associated with a higher stock of soil measured by the shadow price of structures.

The models so far discussed considered crop mix as an exogenous variable and assumed the farmer produces only one crop. Goetz (1997), however, analyzed the optimal and social inter-temporal path of soil use considering crop choice itself as a soil conservation practice in addition to the conventional inputs. The farmer was assumed to maximize the present discounted value of net returns from a choice of an appropriate mix of inputs and crops having differing erosive potential. Goetz's results showed that if farmers recognize the productivity impacts of soil loss and maximize their longrun net returns, the optimal strategy is predominantly characterized by the cultivation of just one crop. At the steady state, however, a mix of crops is cultivated. Comparative analysis of the steady state showed that policies affecting prices have an uncertain effect implying either taxing or subsidizing the price does not seem to be a viable option for improving the longrun soil stock.

Another study worth considering utilizing optimal control model for economic analysis of soil degradation is that of Brekke et al. (1999) who modeled the inter-temporal soil use combining a soil scientific model of soil productivity and degradation with economic variables. Farmers are assumed to maximize soil wealth measured as the present value of soil rent by choosing labor input, capital and fertilizer input. They developed two versions of an optimal control mode: 1) the soil mining model which presupposes soil nutrient mining as the overriding land degradation problem thus treating the soil capital as a renewable natural resource and 2) an expanded model which considers land degradation resulting from both nutrient mining and top soil loss due to erosion. Brekke et al. (1999) model is particularly appealing in that it explicitly recognizes both soil nutrient mining and topsoil loss. However, they did not include soil conservation practices in their model.

More recently, Nakhumwa (2004) employing an inter-temporal optimization framework that included soil conservation practices investigated the impact of soil degradation due to nutrient mining on the productive value of smallholder land in Malawi. The model was constructed on the premise that the impact of irreversible physical soil degradation due to erosion poses less of a threat to smallholder agriculture in Malawi and that there is no significant interaction between fall in soil productivity and erosion induced decline of soil physical structure. The model maximized the discounted sum of the stream of net benefits from the use of soil quality stock to produce agricultural output by choosing optimal levels of fertilizer and labor for production as well as optimal levels of conservation efforts through the choice of labor and capital inputs for conservation. The study revealed that given current farmer production practices, soil degradation due to nutrient mining represents a significant cost to smallholder agriculture in Malawi, which amounts to USD 21 per ha.

All of the models reviewed above have attempted to characterize the factors that should be included in a farm level economic model with various degree of success. The studies share some similarities

- All the studies attempted to ascertain the rationale behind farmers' decision to tolerate a certain amount of erosion;
- Most of the modeling works pertain to the situation of developed countries;
- With few exception many of the works are purely analytical;

- All focused on on-site impacts of soil erosion;
- The objective function in all of the models reviewed is similar, the maximization of a stream of discounted net returns from farming. However, they differ in the choice of the variables and the specification of the soil loss (erosion) function;
- Most previous optimization studies with the exception of Brekke et al. (1999) and Nakhumwa (2004) 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, estimates from these models could be biased either way.

3.4.2 Approaches to modeling adoption of soil conservation and soil nutrient management practices

In developing countries including Ethiopia, a lot of effort and resources have been devoted to generate and disseminate agricultural technologies to smallholder farmers. Despite the efforts, however, adoption of improved production technologies including soil conservation and soil fertility enhancing practices remained low (Yirga et al., 1996; Demeke et al., 1997; Shiferaw and Holden, 1998; Gebre Michael, 1999; Alene et al., 2000; Gebremedhin and Swinton, 2003). Rather, smallholder farmers continued to rely on traditional production technologies, yield levels stagnated at low levels, the soil erosion problem persisted while per capita food production continued to fall as population increased. It was soon realized that soil degradation and its accompanying effect of low productivity is not simply a technical issue, rather complex including socio-economic and behavioral factors and requires a change in approach. Consequently, the need for a systems approach became apparent in order to deal with the complex nature of low and declining agricultural productivity which necessitated biophysical and social scientists to join hands thereby make agricultural research more relevant to the situation of smallholder subsistence farmers (Mekuria, et al., 1992). The role of smallholder farmers in the technology generation and transfer process was formally recognized and took a new precedence known as participatory technology development and transfer; and the need to develop a better understanding of the conditions which encourage adoption of recommended agricultural technologies became a priority.

Following a change in approach and focus, a number of technology adoption studies were initiated and implemented in developing countries including Ethiopia pertaining to production technologies (Kebede, 1990; Yirga et al., 1996; Hassan et al., 1998a; Hassan et al., 1998b; Adesina and Baidu-Forson, 1995; Baidu-Forson, 1999; Alene et al., 2000; Dadi, et al., 2001; Fufa and Hassan, 2003). The attention provided to analysing the determinants of investments in soil conservation by smallholder farmers in Ethiopia, however, remained low (Shiferaw and Holden, 1998).

Feder *et al.* (1985) have summarized the vast amount of empirical literature on production related adoption and indicated that the constraints to adoption of a new technology may arise from many sources, such as lack of credit, inadequate farm size, unstable supply of complementary inputs, uncertainty and risk. Factors conditioning smallholder farmers' investment in soil conservation and soil fertility management summarized in the literature include: perception of the soil degradation problem, profitability of the proposed technology, household and farm characteristics, attributes of the technology and institutional factors such as land tenure, access to markets, information and credit (Ervin and Ervin, 1982; Norris and Batie, 1987; Pagiola, 1996; Shiferaw and Holden, 1998; Hassan et al., 1998a; Hassan et al., 1998b; Lapar and Pandey, 1999; Kazianga and Masters, 2001; Bamire et al., 2002; Gebremedhin and Swinton, 2003; Nakhumwa and Hassan, 2003; Bekele and Drake, 2003). Others have also argued that besides the above factors risk considerations also affect the rate of adoption of an innovation (Grepperud, 1997b; Shively, 2001; Fufa and Hassan, 2003).

Among the noteworthy empirical studies that investigated the factors conditioning smallholder farmers' decision to invest in soil conservation in developing countries include that of Pagiola (1996) in Kenya, Pender and Kerr (1998) in India, Lapar and Pandy (1999) in Philippines, Kazianga and Masters (2001) in Burkina Faso, Nakhumwa and Hassan, (2003) in Malawi, Shiferaw and Holden (1998), Gebremedhin and Swinton

(2003) and Bekele and Drake (2003) in Ethiopia. These studies highlighted the magnitude and direction of influence of factors hypothesized to condition adoption as largely area specific and their importance varied among countries, between agro-ecologies within countries and among sites within agro-ecologies. Attempts to generalize the relative importance of individual constraints across farm groups, regions and countries are thus unlikely to be useful.

Although important contributions have been made by previous adoption studies in identifying the factors constraining smallholder farmers benefiting from recommended technologies and suggesting ways of improving policy design, the studies, however, were not free from limitations. A fundamental problem characterizing all adoption studies is the absence of economic theory that could serve as a basis for the selection of the determinants of technology adoption decision variables. Although in principle a farmer's investment in conservation practices could be derived from the maximization of his/her utility function, the fact that the arguments of the utility function are not known makes derivation difficult (Norris and Batie, 1987).

Ghadim and Pannell (1999) noted that despite the huge number of adoption studies conducted in the last 30 years, the results in the field remained short of expectations. They indicated that most of the statistical models developed have low levels of explanatory power despite the fact that a long list of explanatory variables is used. Furthermore, the results from different studies are often contradictory regarding the importance of any given variable. Ghadim and Pannell (1999) citing Linder (1987) pointed out four shortcomings responsible for the inconsistent results obtained by most of the empirical studies of agricultural innovations:

- Failure to account for the importance of the dynamic learning process in adoption
- Biases from omitted variables
- Poor model specification
- Failure to relate hypotheses to a sound conceptual frame work

The use of binomial and multinomial qualitative choice models in the analysis of adoption of technologies is well established in the adoption literature (Feder et al., 1985). One purpose of qualitative choice models is to determine the probability that an individual with a given set of attributes will make one choice rather than an alternative (Green, 2000). The two most popular functional forms used for adoption models are the probit and the logit models. Dimara and Skuras (2003), however, acknowledging the contributions that previous adoption studies using dichotomous adoption decision models had made for the design of improved policies, they contended that dichotomous adoption models have got inherent weakness. They indicated that despite the fact that most decision-making processes concerning innovation adoption involve a multistage procedure, static adoption models often consider the process as a single stage. Dimara and Skuras (2003) argued that the basic tent of a single stage decision making process characterizing dichotomous adoption decision models is a direct consequence of the full information assumption embedded in the definition[6] of adoption. However, the full information assumption is often violated and hence analysis of the adoption decision using logit, probit and Tobit models may suffer from model misspecification (Dimara and Skuras, 2003).

Over the years a number of authors have tried to overcome these limitations in a number of ways. Notable modifications and extensions of the standard adoption decision model are briefly discussed below:

1. Byerlee and Hesse de Polanco (1986) and Leathers and Smale (1991) suggested a sequential adoption decision model.
2. Ghadim and Pannell (1999) assuming that previous adoption models did not adequately considered the dynamic learning process suggested the use of a dynamic adoption decision model, which includes farmers' personal perceptions, managerial abilities and risk preferences.

[6] According to Feder et al (1985) individual adoption (adoption at the level of the farm or firm) is defined as the degree of use a new technology in the long-run equilibrium when the farmer has full information about the new technology and its potential.

3. Fufa and Hassan (2003) using a stochastic production function showed the importance of risk effects of factor inputs on production behaviour of smallholder maize growers in Ethiopia.
4. Dimara and Skuras (2003) assuming that adoption of innovations involves a multistage process and drawing from literature that quite a good deal of the sample population in previous adoption studies did not have the necessary information and level of awareness concerning the new technology (violating the full information assumption) suggested a partial observability model.
5. Likewise, Gebremedhin and Swinton (2003) recognizing that the decision to invest in soil conservation involves multiple stages and these decisions may be independent (or sequential) suggested the use of a double hurdle model where a logit or probit regression on adoption (using all observations) is fitted followed by the use of a truncated regression on non-zero observations.
6. Hypothesising that the variables determining the probability of using a conservation technology may be different from the factors affecting intensity of use, Nakhumwa and Hassan (2003) used a selective Tobit model to simulate the adoption decision behaviour of smallholder farmers as a two-step process. Empirical results showed that for smallholder farmers in Malawi, the factors that determine the probability of use of a conservation technology (ridge marker) may be different from that determine the intensity of use (Nakhumwa and Hassan, 2003).

3.5 Summary

The notion that soil is a natural resource capital that could provide sustained flows of productive and environmental supporting services over time if managed properly is well recognized in the literature. Furthermore, the potential threat that soil degradation has posed on the income and welfare of smallholder farmers as well as on national food security in SSA is not disputed. However, the magnitude of the threat that soil degradation poses on current as well as future income to individual farmers and the national economy and how best to address the problem is not well known. Consequently, maintaining and improving the quality of soil resources have become an important policy objective particularly in SSA where the majority of the population ekes out its living from working the soil. Apparently, a lot of resources have been devoted to soil degradation control research and development related efforts.

Previous soil degradation control research efforts could be categorized into two. The first category of research includes studies aimed at improved understanding of the technical relationships involved in soil degradation processes (e.g. soil erosion and the physical, chemical and biological properties of soils) as well as among soil quality decline, soil erosion and fall in land productivity. Although, research in this category have made important strides to uncover the relationship between productivity and soil erosion there still remains much uncertainty concerning the magnitude and extent of the relationship due to methodological and empirical difficulties involved in measurement and estimation. The second category of research includes studies on economic costs of soil degradation and hence on the economic benefits of soil conservation. The later category could further be divided into two: those dealing with estimating the economic costs of soil degradation control and those studies dealing with the analysis of the adoption decision making behavior of land users.

The bulk of the studies that have attempted to model the long-term impacts of soil degradation are concentrated in the developed countries. Both positive (econometric) and normative (optimization) models have been developed to estimate and model the economic costs of soil degradation. The positive models, which were mainly static did not account for the inter-temporal use of the soil capital (ignore the dynamic nature of the soil degradation and soil conservation investments). Normative models included static as well as dynamic formulations. Most of the dynamic models were developed under the presumption of the existence of a competitive or near competitive land market rendering them less suitable to the conditions of developing countries where land markets are incomplete or non-existent. Furthermore, despite the fact that both nutrient mining and water induced topsoil loss are important in SSA including Ethiopia, most of the studies with the exception of Brekke et al. (1999) and Nakhumwa (2004) 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). While the former has considered both sources of soil degradation, conservation effort was not explicitly included as a decision variable. The study by Nakhumwa (2004) included soil conservation effort as a decision variable but focused on the reversible feature of soil degradation. Available estimates were therefore useful to the extent that they indicate the magnitude of the problem but could not provide the full costs that continued soil degradation will have on a country's economic development. Hence, there is a need for both theoretical and empirical studies that employ a dynamic optimization framework accounting for both irreversible soil physical degradation and reversible soil nutrient mining in order to assess the inter-temporal trade-offs (the true costs of soil loss incurred relative to the value of output expected) that farmers face in their production decisions in SSA.

Also, despite the large number of adoption studies carried out in SSA, the attention provided to the analysis of soil conservation adoption and soil nutrient management practices to date is minimal. Various authors have pointed out that most of the statistical models developed and used to investigate the adoption decision behaviour of smallholder farmers have low levels of explanatory power despite the fact that long lists of explanatory variables are used. Furthermore, the results from different studies are often contradictory regarding the importance of any given variable mainly due to differences in the types of soil conservation technologies extended to farmers, agro-ecology and socio-economic situations. This inconsistency of results, therefore, underscores the importance of agro-ecology based empirical adoption studies using well-specified adoption decision models. Recognizing the fact that smallholder farmers in the highlands of Ethiopia manage several plots of land and that soil fertility management and soil conservation practices involve choices among several technological options, this study, applied econometric models that account for simultaneity of choices and interdependent decisions.

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:

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

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:

$$Y = f(L_Y, K_Y, SD, N) \qquad (4.3)$$

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):

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

Subject to equations of motion and initial conditions:

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

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

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

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

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:

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

The FOC for this system:

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

$$\frac{\partial \Pi}{\partial L_Y} = e^{-\delta t}P\frac{\partial f}{\partial L_Y} - e^{\delta t}W_L + \lambda\frac{\partial H}{\partial L_Y} - \mu\frac{\partial D}{\partial L_Y} + \mu\frac{\partial M}{\partial L_Y} = 0 \quad (4.14a)$$
$$e^{-\delta t}\left(Pf_{L_Y} - W_L\right) = -\lambda H_{L_Y} + \mu\left(D_{L_Y} - M_{L_Y}\right) \quad (4.14b)$$

$$\frac{\partial \Pi}{\partial K_Y} = e^{-\delta t}P\frac{\partial f}{\partial K_Y} - e^{\delta t}W_K + \lambda\frac{\partial H}{\partial K_Y} - \mu\frac{\partial D}{\partial K_Y} + \mu\frac{\partial M}{\partial K_Y} = 0 \quad (4.15a)$$
$$e^{-\delta t}\left(Pf_{K_Y} - W_K\right) = -\lambda H_{K_Y} + \mu\left(D_{K_Y} - M_{K_Y}\right) \quad (4.15b)$$

$$\frac{\partial \Pi}{\partial L_S} = -e^{-\delta t}W_S + \lambda\frac{\partial H}{\partial L_S} + \mu\frac{\partial M}{\partial L_S} = 0 \quad (4.16a)$$
$$e^{-\delta t}W_S = \lambda H_{L_S} + \mu M_{L_S} \quad (4.16b)$$

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

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

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

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

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.

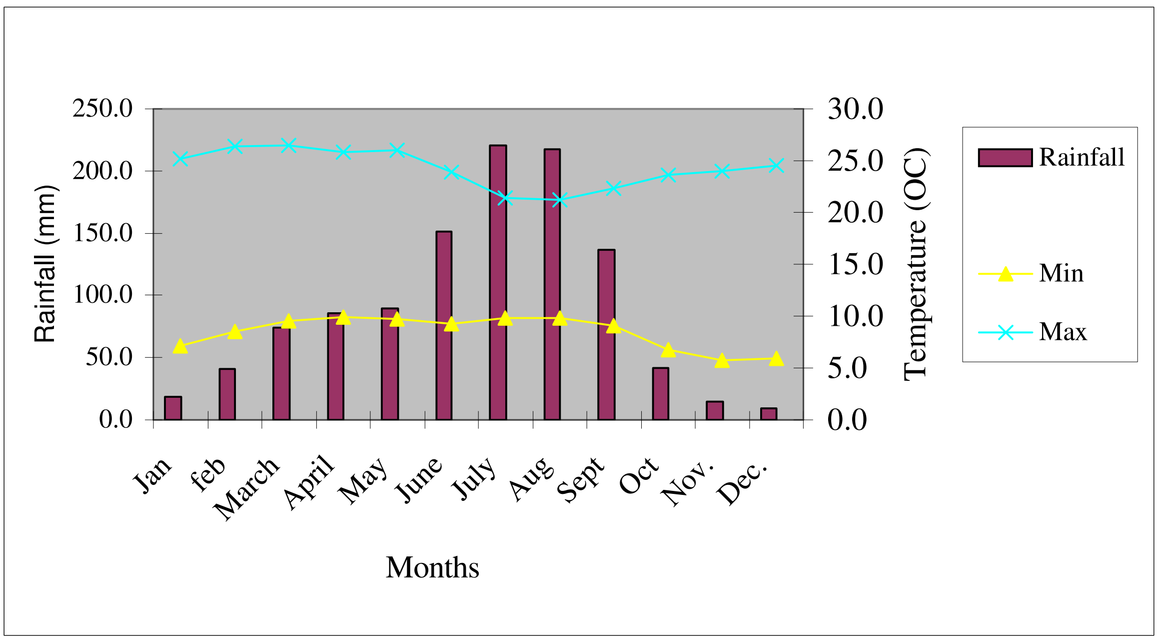

Figure 5.1. Long-term average monthly rainfall and temperature distributions at Ginchi (Dendi district), 1982-2002, Ethiopia.

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.

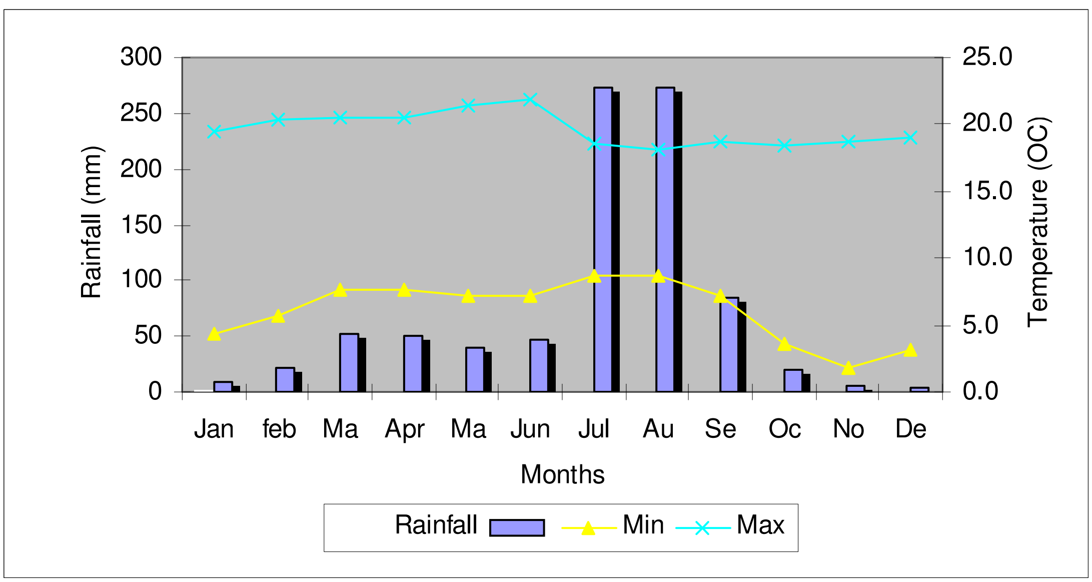

Figure 5.2. Long-term average monthly rainfall and temperature distributions at Debre Birehan, 1982-2002, Ethiopia.

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.

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[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.

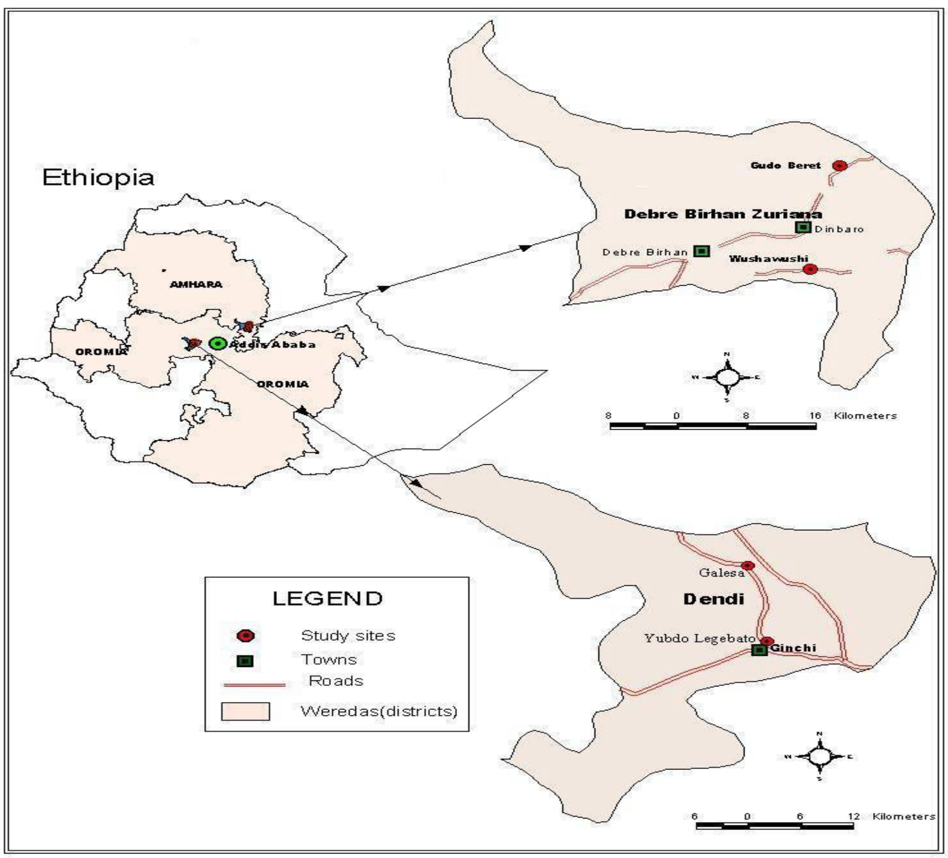

Figure 5.3. Map of the study area.

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.

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

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):

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

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

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

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:

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

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:

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

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:

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

Subject to the equation of motion and initial condition:

$$N_0 = \overline{N} \qquad (6.11)$$

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

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:

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

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 $L_Y^*, K_Y^*, L_S^*, F^*, N^*$ 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 $1 g/cc^3$, 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 ($\beta_1 = 1$), 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

[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% β_1=1 β_2=29.15 β_3=1.7 Z=5	Change in G(F) δ=9% β_1=0.7 β_2=29.15 β_3=1.7 Z=5	Change in output elasticity of N (g) δ=9% β_1=1 β_2=29.15 β_3=1.7 Z=5		Change in output elasticity of SD (d) δ=9% β_1=1 β_2=29.15 β_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.

CHAPTER VII: MODELLING ADOPTION OF SOIL FERTILITY MANAGEMENT AND CONSERVATION PRACTICES

This chapter describes the approach adopted by the study to model adoption of soil fertility management and soil conservation practices by smallholder farmers in the Central highlands of Ethiopia. The first section presents the analytical framework and the empirical models are specified in section two. The last section describes the factors hypothesized to influence adoption behavior of smallholder farmers.

7.1 Analytical framework

The decision whether or not to use a new technology could be considered under the general framework of utility or profit maximization (Norris and Batie, 1987; Pryanishnikov and Katarina, 2003). It is assumed that economic agents including smallholder subsistence farmers use a technology only when the perceived utility or net benefit from using a technology is significantly greater than would be the case without the technology. While utility is not directly observed the actions of economic agents are observed through the choices they make. Suppose that Y_j and Y_k represent a household's utility for two choices, which could be denoted by U_j and U_k, respectively. Following Green (2000) and Pryanishnikov and Katarina (2003) the linear random utility model could be specified as

$$U_j = \beta_j^{'} X_i + \varepsilon_j \text{ and } U_k = \beta_K^{'} X_i + \varepsilon_K \tag{7.1}$$

where U_j and U_k are the perceived utility of technology j and k, respectively, X_i is a vector of explanatory variables that influence the perceived desirability of the technology, β_j and β_k are parameters to be estimated and ε_j and ε_k are the error terms, assumed to be independently and identically distributed. In case of soil fertility and soil conservation technologies, if a household decides to use option j on the i^{th} plot, it follows that the perceived utility or benefit from option j is greater than the utility from other options (say k) depicted as:

$$U_{ij}(\beta_j^{'} X_i + \varepsilon_j) > U_{ik}(\beta_k^{'} X_i + \varepsilon_k), k \neq j \tag{7.2}$$

The probability that a household will adopt option j among the set of soil fertility and soil conservation practices could then be defined as:

$$\begin{aligned} P(Y = 1 \mid X) &= P(U_{ij} > U_{ik}) \qquad (7.3) \\ &= P(\beta_j^{'} X_i + \varepsilon_j - \beta_k^{'} X_i - \varepsilon_k > 0 \mid X) \\ &= P(\beta_j^{'} X_i - \beta_k^{'} X_i + \varepsilon_j - \varepsilon_k > 0 \mid X) \\ &= P(\beta * X_i + \varepsilon^* > 0 \mid X = F(\beta^* X_i) \end{aligned}$$

where P is a probability function, U_{ij}, U_{ik} and X_i as defined above, $\varepsilon^* = \varepsilon_j - \varepsilon_k$ is a random disturbance term, $\beta^* = (\beta_j^{'} - \beta_k^{'})$ is a vector of unknown parameters which can be interpreted as the net influence of the vector of independent variables influencing adoption, and $F(\beta^* X_i)$ is the cumulative distribution function of ε^* evaluated at $\beta^* X_i$. The exact distribution of F depends on the distribution of the random disturbance term, ε^*. Depending on the assumed distribution that the random disturbance term follows, several qualitative choice models such as a linear probability model, a logit or probit models could be estimated (Pindyck and Rubinfeld, 1997; Green, 2000).

Qualitative choice models are useful to estimate the probability that an individual with a given set of attributes will make one choice rather than an alternative (Pindyck and Rubinfeld, 1997; Green, 2000). Of the three functional relationships often specified, the linear probability model is computationally simpler and easier to interpret parameter estimates than the other two models. However, its specification creates estimation problems involving the application of ordinary least squares (OLS) such as heteroscendasticity error terms, predicted values may fall outside the (0,1) interval, and non-normal distribution of the error term. Although, transformation could provide homoscedastic disturbance terms and then apply weighted least square procedures, there is no guarantee that the predicted values will lie in the (0,1) probability range. These difficulties with the linear probability model compelled econometricians to look for alternative model specifications (Pindyck and Rubinfeld, 1997; Green, 2000).

The two most popular functional forms used in adoption modelling are the probit and logit. These models have got desirable statistical properties as the probabilities are bounded between 0 and 1 (Pindyck and Rubinfeld, 1997; Green, 2000).

Apparently, adoption models could be grouped into two broad categories based on the number of choices or options available to economic agents (Pindyck and Rubinfeld, 1997; Green, 2000). In a setting where there are only two technological choices or options designated by J_i=1 if agent i adopts and J_i=0 otherwise would give rise to binomial adoption models whereas choice sets with more than two alternatives would give rise to multinomial adoption models.

As noted earlier, smallholder farmers in the highlands of Ethiopia use a mix of soil fertility management and soil conservation practices. However, most previous technology adoption studies in the country focusing on production technologies did not give due consideration to soil conservation and soil fertility management practices albeit a few soil conservation adoption studies by Shiferaw and Holden (1998) in the Andit Tid area, Central highlands, Gebremedihn and Swinton (2003) in Northern highlands and Bekele and Drake (2003) in Eastern highlands of Ethiopia. Most soil fertility adoption studies in the country focused on inorganic fertilizers either as a component of a package of crop production technologies treating the package as a unit or the components of the package as separate units (Waktola, 1980; Kebede et al., 1990; Yirga et al., 1996; Alene et al., 2000; Dadi, et al., 2001; Regassa, 2001). To smallholder farmers, however, commercial fertilizer is one technological option among the menu of soil fertility management options available. Furthermore, most previous soil fertility management studies were limited by the analytical methods employed in analyzing the adoption behavior of smallholder farmers. Despite the fact that the adoption decision of soil fertility management involves choices among several soil fertility management decisions making the adoption decision inherently multivariate, most studies employed binomial logit/probit and Tobit regression models to investigate the factors determining the adoption decision and the intensity of use of inorganic fertilizers, respectively. Binomial logit and probit models applied at a household or farm level when in fact input use decisions are made at a plot level (due to non-homogeneity of plots managed by households) may not be appropriate. Dorfman (1996) pointed out that the use of bivariate models when in fact the adoption decision involves a set of several technological options excludes useful information contained in interdependent and simultaneous adoption decisions. Furthermore, as has been argued earlier, most previous adoption studies attempting to model the adoption decision assumed the same explanatory variables influence the adoption decision and intensity of use in a similar fashion. In other words, most previous adoption studies assumed a variable that increase (decrease) the probability of use also increase (decrease) intensity of use of a technology. However, Nakuma and Hassan (2003) and Gebremedhin and Swinton (2003) found evidence that the factors determining the decision to adopt and the factors determining intensity or extent of use of a soil conservation technology might be different. Similarly, Katchova and Miranda (2004) showed that farm characteristics affecting decisions to adopt marketing channels differ from those affecting decisions regarding quantity, frequency and contract type. Accordingly, recognizing the fact that soil fertility management and soil conservation practices involve choices among several technological options, this study, applied a multinomial logit model for discreet dependent variables involving several choices. The study also recognized that factors affecting the adoption decision and the intensity of use of soil fertility management practices might be different hence adopted a Tobit model for continuous dependent variables to model the intensity of inorganic fertilizer and stone/soil bund use by smallholder farmers in the highlands of Ethiopia. Furthermore, taking into account that smallholder farmers input use decisions are made at a plot level due to non-homogeneity of plots managed by households, the study modeled the adoption decision at a plot level.

7.2 Soil fertility and soil conservation technologies in the study area

According to what was discussed in preceding sections, in this study, incidence of use of soil fertility management or a soil conservation practice is measured by the proportion of sample households using one management practice or a combination of practices simultaneously on a plot or parcel of land. Similarly, intensity of use of a certain type or mix of soil fertility management or soil conservation practices are measured by mean use rates or proportion of crop area under each option or mix of options (e.g. amount of inorganic fertilizer or length of soil conservation structures constructed per unit area).

The menu of soil fertility management options that smallholder farmers in the highlands could choose from can be categorized into two: introduced or modern (inorganic fertilizers consisting of DAP and Urea) and traditional[24] including seasonal fallowing (weedy fallows), crop rotations involving legume crops, long-term[25] fallowing (*guie*) and animal manure. Noteworthy is that these soil fertility management practices differ considerably in terms of their attributes, timing of costs and benefits. While animal manure and inorganic fertilizers are productivity enhancing inputs that may be applied at various intensities every year, seasonal fallowing and legume rotations could be considered investment decisions with two years of maturity. Smallholder farmers' soil fertility management strategies on a certain plot, therefore, involve a choice among these inputs and agronomic practices either independently or in some combinations. It should be noted that the use of traditional soil fertility management practices unlike inorganic fertilizers do not involve immediate cash outlays by the household but require substantial opportunity costs in terms of foregone output (e.g. seasonal fallowing, planting less productive legume crops) or require additional family labor inputs to transport manure. Therefore, the decisions to fallow a certain plot or include legumes as rotation crops involve weighing current costs against anticipated benefits in the second cropping season.

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[24] A traditional soil fertility management refers to a technological option that has been well recognized as a soil fertility amendment or enhancement practice and used by smallholder farmers for a long period of time.

[25] The use of long-term fallowing, which once was the most important soil fertility management practice particularly in the upper highlands has now declined due to land shortages and hence this practice will not be considered in this modeling endeavor.

Although it is hardly possible to claim that smallholder subsistence farmers actually make marginal calculations in the literal sense, it is apparent that a household deciding to fallow a plot (practice chiflik) [26] this year, incurs costs in terms of foregone output and extra plowings required for land preparation. Likewise, the decision to plant a legume this year involves weighing tradeoffs between foregoing current benefits from planting a preferred, possibly high yielding cereal crop this year against anticipated productivity improvements in the following year as a result of improved soil quality due to investments in legumes the first year. It is, therefore, hypothesized that different factors may condition the use of traditional soil fertility management practices by smallholder farmers.

Similar arguments could also be made on the adoption of inorganic fertilizers or the combined use of inorganic fertilizers with a traditional practice(s). The decision whether or not to use inorganic fertilizer and how much inorganic fertilizer to use among other things depends on the soil fertility management practices used the previous year (whether a plot was fallowed, had manure or planted to a legume) as well as farmer perceptions of inorganic fertilizer as a possible substitute or complementary input to the traditional fertility management practices and inputs. It is therefore hypothesized that the factors that influence the likelihood and intensity of use of inorganic fertilizer by smallholder farmers may differ from those that appear to be significant when several soil fertility management practices are analyzed as a group. In this study, therefore, based on the above framework two soil fertility adoption models are specified. The first model focuses on factors determining the use or non-use of alternative soil fertility management practices (both traditional and modern) on a cropland (plot). Accordingly, alternative soil fertility management options considered include:

i. Seasonal fallowing (SF) alone
ii. Legume rotations (LR[27]) alone

[26] Seasonal fallowing also referred to as *chiflik* or *worteb* is a traditional soil fertility management practice in which part of the land is fallowed for one season and used for crop production the following season.

[27] Legume rotations refer to the practice of growing leguminous crops such as faba beans and field peas in the upper highlands and chick pea, rough pea, lentil and faba bean in mid highlands in rotation with other crops (non-leguminous).

iii. Animal manure (AM) alone
iv. Animal manure in association with SF
v. Animal manure in association with LR
vi. Inorganic fertilizer (IGF) alone
vii. Inorganic fertilizer in association with options one, two or three (IGF+SF/LR/AM)
viii. Continuous cropping without any soil fertility amendment practice (no adoption)

The second model is targeted at determining the factors associated with the intensity of inorganic fertilizer use among smallholder farmers measured in terms of amount of inorganic fertilizer applied per hectare regardless of the use of traditional soil fertility management practices.

Soil conservation practices used on cultivated lands in the highlands include traditional ditches (*boyi*), cut-off drains (*golenta*) and stone and soil bunds. Among these practices, traditional ditches, though widely practiced, are considered more of a production practice for draining excess runoff from a plot than a soil conservation practice and hence excluded from further consideration. Soil and stone bunds constructed by piling earth mounds and rocks (stones), respectively, are viewed to have similar effects. The choice of a stone against a soil bund largely depends on availability of stones in the vicinity. In this study, therefore, both soil and stone bunds are treated as one category. Like the case of soil fertility management, smallholder farmers have to choose from the various soil conservation practices. Hence, the appropriate econometric model would be a multinomial adoption model. Accordingly, choice sets considered in the soil conservation multinomial adoption model include:

i. The use of traditional cut-off drains (*golenta*) only
ii. Terraces (stone and soil bunds) with or with out cut off drains
iii. No soil conservation practice (no adoption)

The models listed above are presented in the following sub-sections.

7.2.1 Multinomial logit models for the adoption of soil fertility and soil conservation technologies

As pointed above, the choice (dependent) variables: soil fertility management and soil conservation practices are discrete with J+1 alternatives (j=0, 1, 2…J). The appropriate econometric model would, thus, be either a multinomial logit (MNL) or multinomial probit (MNP) regression models. Indeed, both MNL and MNP models estimate the effect of explanatory variables on a dependent variable involving multiple choices with unordered response categories (Dorfman, 1996; Long, 1997; Green, 2000). Multiple response (polychotomous) choice models such as MNL and MNP are more desirable compared to their counterparts of binomial logit and probit models in two respects (Wu and Babcock, 1998). It allows exploring factors conditioning both specific management practices (e.g. inorganic fertilizer alone, farmyard manure alone, etc.) as well as combination of management practices (e.g. integrated soil fertility management such as inorganic fertilizer in association with fallow or legume rotations). It also takes care of self-selection and interactions between alternative practices. However, the probit counterpart of a MNL model is rarely used in empirical studies due to estimation difficulties imposed by the need to solve multiple integrations related to multivariate normal distributions (Wu and Babcock, 1998; Pryanishnikov and Katarina, 2003). In this study, therefore, a MNL specification was adopted to model soil fertility and conservation adoption decision behavior of smallholder farmers' involving discrete dependent variables with multiple choices.

Let M_j be the j^{th} soil fertility or soil conservation management technology that a household chooses to use on the i^{th} plot. M_{ji} could then take the value of 1 if the j^{th} practice or option is adopted on the i^{th} plot, 0 otherwise. The probability that a household with characteristics X adopts technology j on the i^{th} plot is specified as (Green, 2000):

$$P_{ji} = \Pr ob(M_{ji} = 1) = \frac{e^{x'\beta}}{1 + \sum_{j=1}^{J} e^{x'\beta}}, \; j = 1 \ldots J \qquad (7.4)$$

where β is a vector of parameters which satisfy $\ln(P_{ij} / P_{ik}) = X'(\beta_j - \beta_k)$ (Green, 2000).

Unbiased and consistent parameter estimates of the MNL model in equation (7.4) require the assumption of independence of irrelevant alternatives (IIA) to hold. More specifically, the IIA assumption requires that the likelihood of using a certain soil fertility or soil conservation practice on one plot by a household need to be independent of alternative soil fertility and conservation practices on other plots (i.e., P_j / P_k is independent of the remaining probabilities). The premise of the IIA assumption is that of independence and homoscedastic disturbance terms of the basic adoption model in equation (7.1). Wu and Babcock (1998) indicated that the IIA assumption, though, a convenient property with regard to estimation imposes a restriction on farmer behavior. This is particularly true for the study sample where the management decisions made by the same farmer on different plots under his/her management are unlikely to be independent rendering the error terms to correlate.

The validity of the IIA assumption could be tested using Hausman's specification, which is based on the fact that if a choice set is irrelevant, eliminating a choice or choice sets from the model altogether will not change parameter estimates, systematically. The statistics of Hausman's specification is given by (Green, 2000):

$$\chi^2 = (\hat{\beta}_s - \hat{\beta}_f)'[\hat{V}_s - \hat{V}_f]^{-1}(\hat{\beta}_s - \hat{\beta}_f) \qquad (7.5)$$

where s indicates the estimators based on restricted subsets, f indicates the estimator based on the full set of choices, and $\hat{V}_s$ and $\hat{V}_f$ are the respective estimates of the asymptotic covariance matrices.

Alternative models and econometric procedures have been suggested to overcome the limitations of the IIA assumption in the MNL model. Two of such models discussed in the literature are the nested logit and multinomial probit models (Wu and Babcock, 1998; Green, 2000; Heinrich and Wenger, 2002). The nested logit model is widely used in transport and marketing research where the implied decision choices allow specification of a nesting structure or sequencing of decisions. In this study, however, the nested logit model could not be used for there is no a priori specification of a nesting structure of the decision choices made by households. The MNP model, on the other hand, does not require either nesting nor impose no correlation of error terms. However, the computational difficulties involved with estimation limit its application. Heinrich and Wenger (2002) based on a review of the works of James J. Heckman and Daniel L. McFadden suggested a practical way of overcoming the IIA problem in empirical estimation of the MNL model would be to redefine or restructure the choice variables by collapsing closely related choices into distinct groups. In the absence of alternative specifications, this study used the MNL specification to model smallholder farmers' adoption behavior of soil fertility and conservation management practices in the highlands of Ethiopia.

Provided that the IIA assumption is met, the maximum likelihood estimators are asymptotically normally distributed with a mean of zero and a variance of one for large samples (Long, 1997). Nonetheless, the use of cross-section data to estimate model parameters may still introduce heteroscendasticity problems. Upon ascertaining the validity of the IIA assumption, the Huber/White/sandwich estimator of variance instead of the traditional variance estimators can be used to account for possible heteroscendasticity of unknown form. Further improvements of parameter estimates could also be achieved by correcting the variance-covariance (VCE) matrix of the estimators for possible correlation of errors within groups (clusters). Significance of estimators is tested with z-statistics and goodness of fit of the model is assessed by the likelihood-ratio (LR) tests comparing the log-likelihood from the full model (the model with all the explanatory variables) with a restricted model where only the constant is included.

Parameter estimates of the MNL model provide only the direction of effect of the independent variables on the dependent (response) variable but estimates neither represent actual magnitude of change nor probabilities. Differentiating equation (7.4) with respect to each of the explanatory variables, however, provides marginal effects of the explanatory variables given as:

$$\frac{\partial P_j}{\partial x_k} = P_j(\beta_{jk} - \sum_{j=1}^{J-1} P_j \beta_{jk}) \qquad (7.6)$$

The marginal effects or marginal probabilities are function of the probability itself which when multiplied by 100 measure the expected change in probability of a particular choice being made with respect to a unit change in an independent variable (Long, 1997; Green, 2000; Ersado et al., 2004).

7.2.2 Tobit and Heckman's two-step regression models for the intensity of use of inorganic fertilizers and stone/soil bunds

The intensity of use of inorganic fertilizers and stone/soil bund measured as the sum[28] of diamonium phosphate (DAP) and Urea fertilizers applied per unit of cropped area and length of stone/soil bunds, respectively, are censored continuous variables. As discussed above, this censoring arises due to the fact that not all sample households use inorganic fertilizers or stone/soil bunds. Even those households who reported having used inorganic fertilizer and constructed stone/soil bunds may not have done so on all of the plots under their management. Application of ordinary least square (OLS) to such censored data renders the estimates biased. Two approaches suggested and often used in the literature to overcome the problem are Heckman's two-step procedure (and its extensions thereof) and the Tobit model (Winship and Mare, 1992; Long, 1997; Vella, 1998). This study, therefore, adopts these approaches to model the intensity of inorganic fertilizer and stone/soil bunds among smallholder farmers in the Ethiopian highlands.

[28] DAP and Urea are considered as complementary inputs that should be used in certain combinations depending on crop type and soil characteristics. Despite research recommendations emphasizing use of recommended rates of both DAP and Urea for maximum yield, most smallholder farmers prefer DAP to Urea and use more DAP than Urea but at sub-optimal levels.

The Tobit model, a more general case of probit, besides the probability of adoption as in the probit model estimates the value of the continuous response for the case when

$$y_i^* = \beta' x_i + \varepsilon_i \tag{7.7}$$

Where X_i is an N * 1 vector of explanatory factors, β is a vector of coefficients, and ε_i are independently and normally distributed error term with mean zero and variance, σ^2. If y_i^* is negative, the variable that is actually observed, the rate of commercial fertilizer or length of stone/soil bund, y_i is zero. When y_i^* is positive, $y_i = y_i^*$.

Following Long (1997) and Green (2000), the probability that the rate of inorganic fertilizer or stone/soil bund used is zero in the Tobit model could be specified as:

$$P(y_i = 0) = \phi(-\frac{\beta' x_i}{\sigma}) \tag{7.8}$$

and the density function for the positive values of Y_i is

$$f(y_i / y_i > 0) = \frac{f(y_i)}{P(y_i > 0)} = \frac{\frac{1}{\sigma}\phi(\frac{y_1 - \beta' x_i)}{\sigma}}{\phi(\frac{\beta\, x_i}{\sigma})} \tag{7.9}$$

where $\phi(\bullet)$ is the standard normal probability density function. Equation (7.8) is a probit model representing the adoption decision whereas equation (7. 9) represents a truncated regression for the positive values of the continuous decision of how much soil fertility inputs to use $(y_i > 0)$. The Tobit model is preferable to OLS for it allows the inclusion of observations with zero values. Both the probit and Tobit models require maximum likelihood methods (MLE) to estimate the coefficients of the adoption equation. The log-likelihood for the Tobit model consists of the probabilities for the non-adoption decision and a classical regression for the positive values of Y_i (Long, 1997) given by:

$$\ln L = \sum \ln \phi(-\frac{\beta' x_i}{\sigma}) + \sum \ln[\frac{1}{\sigma}\phi(\frac{y_i - \beta_i' x_i}{\sigma})] \quad (7.10)$$

The estimated coefficients, β, do not represent the marginal effects of a unit change in the independent variable on E(Y) or E(Y^*). Based on the works of McDonald and Moffit, Long (1997), Green (2000) and many others showed the following decomposition of the marginal effects of the Tobit model:

$$\frac{\partial E(Y/X)}{\partial X_j} = \Pr(Y>0)\frac{\partial E(Y \mid Y>0)}{\partial X_j} + E(Y/Y>0)\frac{\partial \Pr(Y>0)}{\partial X_j} \quad (7.11)$$

where Pr(Y>0) is the probability of an observation being uncensored given X. The above decomposition shows that the total change in the unconditional expectation is disaggregated into the change in conditional intensity of use weighted by the probability of adoption and the change in the probability of adoption weighted by the conditional intensity of use.

A major concern with the ML estimators of the Tobit model is its sensitivity to violation of the basic assumptions of homoscedasticity and normality of the errors (Long, 1997; Vella, 1998; Green, 2000). Violation of these assumptions renders the Tobit estimates biased and inconsistent (Long, 1997; Vella, 1998; Green, 2000). The incidence of heteroscendasticity in the Tobit model could be detected using a likelihood ratio and/or a Lagrange multiplier test (Green, 2000). As recommended for the MNL model, in the Tobit model too, the Huber/White/sandwich estimator of variance could be used to correct for possible heteroscendasticity of unknown form.

Test for the non-normality of the disturbance terms in the Tobit model, however, is not straightforward. Green (2000) suggested alternative approaches to deal with the non-normality of the error distribution in the Tobit model. One way is to assume alternative forms of the error distribution (exponential, lognormal and Weibull) and compare results. Another approach is to use robust estimators less sensitive to changes in the distribution of the error terms such as least absolute deviations (LAD) and censored least absolute deviations estimators (CLAD). Empirical application of semi parametric models, however, is limited due to computational complexity and hence is not pursued in this study.

A second concern in the proposed Tobit model particularly for the intensity of fertilizer use is endogeneity. Besides household, farm, plot and institutional variables hypothesized to condition inorganic fertilizer use, soil fertility management practices used the previous season (fallow, legume or farmyard manure) are believed to be important in explaining variations in inorganic fertilizer use among smallholder farmers. These variables are thus included as explanatory variables in the Tobit model. One would argue inclusion of these variables in the right hand side of the equation might result in biased and inconsistent parameter estimates due to endogeneity. In principle, the endogeneity problem could be adequately dealt with a two-stage model or using instrumental variable technique (Hassan, 1996). The problem for our data, however, is not expected to be serious as the decision to use inorganic fertilizer and other soil fertility management practices are not made at the same time. As has been noted earlier, the decisions whether or not to use inorganic fertilizer and how much inorganic fertilizer to use on a plot given the farmer has decided to cultivate the plot in question is made at planting. On the other hand, the decisions to fallow, use legume rotations or apply farmyard manure are already taken prior to plating either in the previous season or during the off-season.

A third concern with the Tobit specification is whether or not it adequately fits the data. The Tobit model is based on the assumption that there is no sample selection problem. In the presence of self-selction, however, results of the Tobit model are biased and inconsistent (Winship and Mare, 1992; Vella, 1998). Furthermore, the Tobit model assumes that a variable that increases the probability of adoption will also increases the mean amount of inputs used (Lin and Schmidt, 1984; Norris and Batie, 1987; Katchova and Miranda, 2004). The preposition that the same variables and the same parameter vector affect both the adoption decision and the intensity of use, however, has been questioned (Green, 2000; Gebremedhin and Swinton, 2003; Katchova and Miranda, 2004). Lin and Schmidt (1984) proposed a formal procedure to test the validity of the Tobit assumption. This test explores whether a censored Tobit model fits the data better compared to a separate probit and a truncated regression (a Tobit which only uses non-limit cases for the dependent variable) by computing the following likelihood ratio statistic (Lin and Schmidt, 1984; Green, 2000):

$$\lambda = -2[\ln L_T - (\log L_{\mathrm{P}} + \log L_{TR}) \quad (7.12)$$

where λ is distributed as chi-square with R degrees of freedom (R is the number of independent variables including a constant), L_T is a likelihood function for the Tobit model with the same coefficients, L_P is a likelihood function for the probit model fit separately, and L_{TR} is likelihood for the truncated regression model fit separately. If the null hypothesis is rejected, Heckmans's (1979) two-step procedure, which allows for different factors to influence the adoption decision and intensity of use would be appropriate.

Hickman's two-step procedure described below involves estimation of the probability model for the adoption decision, calculation of the sample selection bias (the inverse Mill's Ratio) and incorporation of this selectivity bias variable into the outcome equation (intensity of use) and then apply OLS to estimate the intensity of use.

The first procedure in Heckmans's to step model is to estimate a probit model for the probability that Z=1 with all observations using a set of covariates (ω) to estimate a vector of coefficients (α) given by.

$$P_i(Z_i = 1) = \phi(\varpi_i^{'}\alpha) + e_i \quad (7.13)$$

The second procedure would be to estimate the expected value of the outcome variable (Y) conditional on Z=1 and a set of covariates (X_i).

$$E(Y_i \mid z = 1, X_i) = X_i^{'}\beta + E(\mu_i \mid Z_i) \quad (7.14)$$

The third procedure is to evaluate the conditional expectation of μ in equation (7.14) with respect to the variable, e, represented by

$$E(\mu_i \mid e_i)\omega_i^{'}\alpha = \rho\sigma_e\sigma_\mu \frac{\phi(\omega_i^{'}\alpha)}{\Phi(\omega_i^{'}\alpha)} \tag{7.15}$$

Then, inserting equation (7.15) into equation (7.14) we get equation (7.16) as follows:

$$E(Y_i \mid z = 1, X_i) = X_i^{'}\beta + \rho\sigma_e\sigma_\mu \frac{\phi(\omega_i^{'}\alpha)}{\Phi(\omega_i^{'}\alpha)} \tag{7.16}$$

Finally, we use OLS to regress Y on X and $\lambda_i \frac{\phi_i}{\Phi_i}$ given by:

$$E(Y_i \mid Z = 1, X_i) = X_i^{'}\hat{\beta} + \theta\hat{\lambda}_i \tag{7.17}$$

7.3 Choice of variables and hypotheses to be tested

As noted above, the adoption behaviour of farmers could be traced from their utility functions. However, the fact that the arguments of the utility function are not well known makes selection of the determinants of technology adoption a difficult task (Norris and Batie, 1987; Shiferaw and Holden, 1998). Previous research on farmers' adoption of new technologies including soil conservation considered perception of the problem or constraint (soil degradation), profitability of the proposed technology, household and farm characteristics, attributes of the technology and institutional factors such as land tenure, access to markets, information and credit (Ervin and Ervin, 1982; Norris and Batie, 1987; Pagiola, 1996; Shiferaw and Holden, 1998; Hassan et al., 1998a; Hassan et al., 1998b; Lapar and Pandey, 1999; Kazianga and Masters, 2002; Bamire et al., 2002; Gebremedhin and Swinton, 2003; Nakhumwa and Hassan, 2003; Bekele and Drake, 2003). Shiferaw and Holden (1998) argued that the effect of most of these factors on adoption behaviour of farmers is conditioned by market imperfections prevalent in developing countries including Ethiopia. Where market imperfections are important the production and consumption decisions of smallholder farmers may not be separable making indispensable the inclusion of household characteristics, asset endowments, institutional factors and other variables impacting profitability of the proposed technology as explanatory variables in the adoption decision model (Shiferaw and Holden, 1998). Therefore, based on investment theory, previous studies and analysis of the agriculture sector of Ethiopia, a range of household, farm and plot characteristics, institutional factors and agro-ecology variations are hypothesized to influence adoption of soil fertility management and soil conservation technologies by smallholder farmers in the highlands of Ethiopia.

7.3.1 Household characteristics

Household attributes often considered to have differential impacts on the adoption decision include age, education level of the household head, family size and wealth (livestock ownership and type of house).

Several studies considered the effect of age of the farmer on adoption decision as a composite of the effects of farming experience and planning horizon. Many equated short planning horizons with older, more experienced farmers who may be reluctant to adopt soil conservation practices that may not yield immediate benefits whereas younger farmers being more educated on the average and having longer planning horizons may be more likely to invest in soil conservation (Norris and Bati, 1987; Lapar and Pandey, 1999). On the other hand, greater experience could lead to better knowledge of spatial variability of plots that could lead to more accurate assessment of adoption. Several studies in Ethiopia have shown a positive relationship between number of years of experience in agriculture and the adoption of improved agricultural technologies, Kebede et al. (1990), while a study by Shiferaw and Holden (1998) indicated a negative relationship between age and adoption of improved soil conservation practices. Hence, considering the above factors the effect of age of the household head, a proxy for years of experience in farming, cannot be signed in the empirical model a priori.

Higher education is believed to be associated with access to information on improved technologies and the productivity consequences of land degradation (Ervin and Ervin, 1982; Feder et al., 1985; Norris and Bati, 1987). Evidence from various sources indicates a positive relationship between the educational level of the household head and the adoption behaviour of farmers (Norris and Bati, 1987; Igoden et al., 1990; Lin, 1991), as well as literacy and adoption behaviour (Yirga et al., 1996). Farmers with higher levels of education, therefore, are more likely to adopt land augmenting soil fertility and soil conservation technologies than those who do not.

The influence of household size on the decision to adopt is ambiguous. Large family size is normally associated with a higher labor endowment that would enable a household to accomplish various agricultural tasks on timely bases. On the other hand, households with large family members may be forced to divert part of the labor force to off-farm activities in an attempt to earn income in order to ease the consumption pressure imposed by a large family size. In the highlands of Ethiopia, off-farm opportunities are rare especially during the slack period of the year after the main season harvest when conservation activities are expected to be performed implying low opportunity cost of labor during this period. Hence, we expect a household with large family size to be more likely to adopt land augmenting soil fertility management practices such as inorganic fertilizer and manure especially soil conservation practices involving labor-intensive constructions but inversely related to the use of seasonal fallowing.

Wealth is believed to reflect past achievements of households and their ability to bear risk. Previous studies in Ethiopia used the type of house a household owns (corrugated or grass roofed) and the number of livestock as a proxy for the wealth position of a household (Yirga et al., 1996; Shiferaw and Holden, 1998). Livestock plays a very important role in the mixed crop-livestock farming systems of the highlands. First, it serves, as a store of value, which could be easily traded to meet a household's cash needs in time of emergencies. Second, oxen being the major source of traction power play a crucial role in timely land preparation and planting that consequently improves the marginal productivity of soil fertility inputs. Third, livestock provides manure required for soil fertility maintenance. Therefore, the number of livestock owned is hypothesized to be positively associated with the adoption of soil fertility and soil conservation technologies.

7.3.2 Farm and plot characteristics

Farm characteristics hypothesized to influence adoption in this study are farm size, number of plots (parcels) owned and distance of plots from the homestead. Smallholder farmers in the highlands manage several plots of land scattered across a topo-location. These plots not only vary in size but also differ in soil types, fertility levels, degree of slope and other plot specific features. Obviously, adoption of soil fertility and soil conservation practices would be a function of plot characteristics as these factors influence actual and perceived levels of soil degradation as well as actual and perceived costs and benefits.

Norris and Batie (1987) indicated that farmers who own and cultivate larger farms are likely to spend more on conservation as it is associated with greater wealth and increased availability of capital, which makes investment more feasible. The impact of farm size could, however, vary depending on the type of soil fertility management and conservation practices considered. Households with relatively larger farm size may prefer seasonal fallowing to more intensive forms of soil fertility management and conservation practices while land scarce households might have incentives to adopt labor intensive management practices. A study by Negatu and Parrikh (1999) revealed a positive impact of farm size on adoption of improved wheat and maize varieties, respectively, whereas Yirga et al., (1996) reported no association between land per person and the use of crop technologies including commercial fertilizer. Hence, the impact of farm size on the adoption decisions could not be predicted a priori.

Other things being equal, the larger the plot slope the higher the erosion hazard. Slope of a plot is therefore expected to have a positive association with the use of soil conservation practices.

Ervin and Ervin (1982) and Norris and Batie (1987) noted perception of an erosion problem is the first step in the adoption process, which triggers subsequent adoption. Recognition of erosion has been found to positively influence conservation behavior in a number of studies (Shiferaw and Holden, 1998; Bekele and Drake, 2003). Hence, it is expected that households who manage marginal plots (plots with poor soil fertility) or face the most sever potential erosion problems are more likely to adopt soil fertility and soil conservation practices.

Distance of a plot from a household's residence may influence a households investment decisions in two ways. First, distance of a plot by raising the labor costs for hauling manure and the opportunity cost of labor (time lost traveling to and from a plot) may have a disincentive on investments in soil nutrient management and soil conservation technologies involving substantial labor inputs. Secondly, plots located far from farmers' residences are high-risk investments as the chance of loosing these plots is higher in the event of land redistribution. Hence, plot distance is expected to be negatively associated with the use of animal manure and legume rotations, which require at least two years to realize the benefits, but positively with the use of inorganic fertilizer.

The physical size of a plot may have a range of influence on the adoption decision of soil fertility and soil conservation practices. For instance, the area taken up by soil conservation structures might potentially reduce crop output and may eventually discourage adoption of soil conservation structures. On relatively large plots, a household may not be concerned with the potential area loss due to adoption of soil conservation and subsequent reduction of crop output compared to small sized plots. Physical structures on small plots of land also cause inconveniencies for using oxen during ploughing (Shiferaw and Holden, 1998). Hence, the potential impact of plot size on the adoption of soil fertility management and soil conservation would be different. Plot size is expected to be inversely related to the adoption of land augmenting soil fertility management practices (commercial fertilizer and manure use) but positively related to seasonal fallowing and soil conservation practices.

7.3.3 Institutional factors

Institutional factors often considered in empirical adoption decisions to have differential impacts on technology adoption by smallholder farmers are access to information, institutional credit, off-farm employment and land tenure. Direct government involvement in the construction of soil and water conservation structures on farmers field has also been cited to have a considerable impact on the adoption decision (Gebremedihn and Swinton, 2003; Bekele and Drake, 2003)

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Access to information on sources of new inputs is believed to contribute towards optimal use of scarce resources. Various studies in developing countries including Ethiopia reported a strong positive relationship between access to information and the adoption behaviour of farmers (Kebede et al., 1990; Yirga et al., 1996; Ghadim and Pannell, 1999; Herath and Takeya, 2003). In Ethiopia, agricultural extension services provided by the MOA is the major source of extension information in general and in the study area in particular. Hence, it is hypothesized that the greater the number of contacts a household has with extension workers, the more likely the adoption decision.

The role of off-farm income on the decision to adopt is not clear. It is observed that farmers with off-farm income are less risk-averse than farmers without sources of off-farm income. Off-farm activities may also reduce the management resources available for the adoption process, but access to outside information may have positive effects. Norris and Batie (1987) found a negative association between off-farm employment and adoption of conservation adoption in the US. Hence, the impact of off-farm income on adoption could not be predicted a priori.

There is mixed evidence about the impact of land ownership on incentives to adopt a new technology. Tenure status affects investments in soil conservation by altering the planning horizon (Lapar and Pandey, 1999). A number of studies showed that land ownership increase incentives by lengthening planning horizons and the share of benefits accruing to adopters while lowering the rates of time preference. Others argue that the effect of tenure on adoption depends on the type of technology in consideration. A technology with a high potential to conserve input use, reduce cost, and provide economic benefits such as conservation tillage could create incentives for adoption even among renters, part time renters and part time operators (Norris and Batie, 1987). Nonetheless, it is generally held that renters of farmland are less likely to invest in conservation practices because short-term leases reduce incentives to maintain the productivity of rented land (Norris and Batie, 1987; Soule et.al, 2000). In Ethiopia, despite the fact that land is a public property under the custody of the government, informal land markets have thrived where smallholder farmers either lease land in cash or on share cropping bases (Teklu and Lemi, 2004). Nevertheless, given past experience and the widely held view that land redistribution is a fact of life as long as land remains a public property, there still remains much uncertainty concerning tenure security. It is therefore hypothesized that adoption of soil fertility management practices that yield benefits over a couple of years such as animal manure and seasonal fallowing as well as conservation practices are expected to be used more likely on owned plots (plots allotted to a household directly by PA officials) than on rented or share cropped plots.

Liquidity constraint (cash shortages) is a typical feature of smallholder farmers operating in developing countries. Availability of agricultural credit by easing the liquidity constraint allows smallholder farmers to have access to external purchased inputs such as commercial fertilizer and other new agricultural technologies, which ultimately improve farm productivity. Studies by Zeller et al. (1996), Yirga et al. (1996), Hassan et al. (1998a) underscored the role of credit in enhancing adoption of agricultural technologies. It is therefore hypothesized that access to credit will have a positive impact on adoption of both soil nutrient and soil conservation technologies.

Soil conservation practices have been promoted and in some cases constructed by direct public interventions on farmers' fields. On-farm demonstrations of improved varieties with their associated cultural practices have also been held to demonstrate the superiority of improved technologies over traditional practices. Hence, it is hypothesized that households who benefited from direct public intervention or participation in demonstrations and extension package programmes may have developed a positive attitude towards improved soil management practices.

7.3.4 Agro-ecology

The highlands of Ethiopia are characterized by diverse climate, land use and settlement patterns. Within the central highlands a number of sub agro-ecologies or farming systems have been identified based on variations in altitudes, rainfall, soil type, topographic conditions and type of associated vegetative cover. Earlier studies indicated that while the sub agro-ecologies are similar in some features they exhibit marked differences in terms of soil types, cropping pattern and soil management practices used by farmers that have a strong bearing on the adoption of soil conservation and soil fertility management practices. The upper highlands being cooler and frost prone are better suited to long cycle (season) crops and crop varieties such as oats and six rowed barley varieties. The mid highlands on the other hand are relatively warmer and less susceptible to frost and hence are favorable for growing tef and wheat, the two most important cash sources to smallholder farmers in the highlands. Besides, wheat and tef are reported to have a better response to inorganic fertilizers than barley making the use of inorganic fertilizers more profitable on wheat and tef than barley. Therefore, it is hypothesized that the probability and intensity of inorganic fertilizer use would be higher in the mid highlands where wheat and tef dominate the cropping system than the barley based farming systems of the upper highlands. On the other hand, in the upper highlands where intensive and continuous crop cultivation is less attractive compared to the warmer mid highlands, smallholder farmers tend to keep relatively larger livestock than their counterparts in the mid highlands. Hence, it is hypothesized that the probability of using manure alone or in combination with other soil fertility management practices is likely to be higher in the upper highlands.

Table 7.1. Definition of variables hypothesized to condition adoption of soil fertility management and soil conservation practices by smallholder farmers in the Central highlands of Ethiopian, 2003

Variable	Description	Values
HH characteristics		
Age	Age of the head of the farm HH	Years
Education	Level of formal schooling attained by the head of the HH	Highest grade attend
Livestock	Number of livestock owned by a HH	Number in TLU
House type	Whether a HH owned corrugated iron roofed house or not	1= yes, 0=no
Family size	Number of family members of a HH	Number
Farm and plot characteristics		
Farm size	Total area (crop, fallow, grazing) managed by a HH	Area in hectares
Plot area	The physical size of a plot	Area in hectares
No. of plots	Plots owned and managed by a HH	Number
Plot distance	The distance of a plot from homestead	Minutes walked
Slope	Slop of a plot	1=flat, 2=medium, 3=high
Soil fertility	Farmer perception of the level of soil fertility of a plot	1=poor, 2=medium, 3=fertile, 4=manured (kossi)
Degradation	Farmer perception of the severity of soil loss on a plot	1=none, 2=light, 3=sever, 4=very sever
Institutional factors		
Extension	If HH has access to extension services	1= yes, 0=no
Assistance	If HH had received assistance from government/NGO for constructing conservation structures	1= yes, 0=no
Credit	If a HH had access to institutional credit for inorganic fertilizer	Amount of money borrowed (Birr[29])
Off-farm	Income from off-farm activities during the survey year	Estimated average income (Birr/year)
Tenure	If plot is owned (allotted to HH by PA) or rented/share cropped	1=owned, 0=otherwise
Agro-ecology	Upper highlands or mid highlands	1=upper highlands, 0=mid highlands
District	Dendi and Debre Berihan	1=Debre Berihane 0=Dendi

HH=household

[29] Local currency, 1USD=8.6 Ethiopian Birr

CHAPTER VIII: FACTORS INFLUENCING ADOPTION OF SOIL FERTILITY MANAGEMENT AND SOIL CONSERVATION PRACTICES

This chapter applied the econometric adoption models specified in chapter 7 to analyze factors determining adoption of soil fertility management and soil conservation practices by smallholder farmers in the Central highlands of Ethiopia. Section one presents the econometric procedures followed to estimate model parameters discussed in subsequent sections. Sections two and three discuss empirical results of the econometric analyses of the factors determining adoption of soil fertility management and soil conservation practices, respectively. The last section summarizes the findings and implications of the empirical results.

8.1 Empirical parameter estimation procedures

This section discusses econometric procedures used to estimate model parameters based on the frameworks developed in the previous chapter. Two multinomial logit (MNL) models for the discrete dependent variables of soil fertility and soil conservation practices and two Tobit models for the intensity of inorganic fertilizer and stone/soil bunds are estimated. All analysis is based on pooled data from the Debere Birehan and Dendi districts.

In empirical adoption studies involving cross-section data multicollinearity often poses a major econometric challenge. Hence, as a first step, prior to estimating any of the adoption models, the independent variables were scrutinized for possible strong correlations among them. Among the variables hypothesized to influence adoption behaviour, age of the head of the farm household was found to be correlated with education level of the household head (ρ=0.29), farm size (ρ=0.26) and number of livestock owned (ρ=0.22). Farm size was also found to be correlated with plot area (ρ=0.39), number of plots (ρ=0.17) and number of livestock owned (ρ=0.31). Although these correlation coefficients do not suggest incidence of strong multicollinearity, initial runs of the models revealed that parameter estimates of age and farm size were consistently insignificant and hence dropped from further consideration. Farmer perception of the severity of soil degradation showed a high degree of correlation with various plot attributes: soil depth, level of soil fertility and potential productivity and hence the later were excluded from the final regression equations. Similary, district was found to be highly correlated with agroecology (ρ=0.64) and hence either district or agroecology were included as regressors in the estimated models.

In all models (both MNL and Tobit specifications) robust standard errors of the Huber/White/sandwich estimators of variance are used to correct for possible heteroscendasticity of unknown form (White, 1980; Vella, 1998). Furthermore, the variance covariance matrix is modified to account for the non-independence of observations from different plots under the management of the same household through clustering. All models were estimated by Stata version 8.0. Model specific specification tests (the IIA assumption for the MNL models and sensitivity of parameter estimates to alternative distributional assumptions of the error term for the Tobit models) are discussed in the respective sections along with empirical model results.

8.2 Results of the empirical analyses of determinants of the use of soil fertility management practices

8.2.1 Adoption rate and pattern of soil fertility management

The study revealed that smallholder farmers in the central highlands used four types of soil fertility management (SFM) practices namely seasonal fallowing (fallow rotations, SF), legume rotations (LG), animal manure (AM) and inorganic fertilizers (IGF) and their combinations at various intensities. As shown in Table 8.1, while SF and LR are dominant in the upper highlands, IGF alone or combined with traditional practices appears to be the most important practice in the mid highlands. Animal manure singly or in association with other practices is equally important in both the upper and mid highlands. The data further showed that wheat and tef were the priority crops receiving inorganic fertilizer. About 95% and 92% of the wheat and tef plots, respectively, were fertilized in the mid-highlands (Table 8.2).

Table 8.1. Soil fertility management practices used by smallholder farmers for crop production in the Central highlands of Ethiopia (% of plots receiving treatment), 2003

Soil fertility management practice	Agro-ecology		Whole sample (N=1411)
	Upper highlands (N=1099)	Mid highlands (N=312)	
Continuous cropping without soil fertility amendment practice	23.1	25.6	23.7
Single management practice			
Fallow rotation (SF)	19.5	0.0	15.2
Legume rotations (LR)	17.6	2.9	14.3
Animal manure (AM)	15.9	18.9	16.6
Inorganic fertilizer (IGF)	3.2	28.8	8.9
Multiple practices	6.8	2.2	5.8
AM+SF	1.5	0.3	1.3
AM+LR	5.3	1.9	4.5
Integrated SFM practices	13.9	21.5	15.6
IGF+SF	8.1	1.0	6.5
IGF+LR	3.7	17.6	6.8
IGF+AM	1.4	1.9	1.5
IGF+AM+SF	0.5	0.0	0.4
IGF+AM+LR	0.2	1.0	0.4

Source: Farmer survey

Furthermore, the data revealed that intensity of inorganic fertilizer use is highest in the mid highlands, with the bulk used on wheat and tef. These findings support the hypothesis that inorganic fertilizers are widely used in the more favorable areas of the mid highlands where wheat and tef are grown mainly for cash. However, average rate of use, particularly for the mid-highlands, was below the recommended[30] level. Previous inorganic fertilizer adoption studies attributed the sub-optimal rate of use to inadequate supplies, late availability and the risk aversion behaviour of farmers (Yirga et al., 1996; Demeke et al, 1997; Croppenstedt et al., 2003). Determinants of alternative soil fertility management practices and intensity of inorganic fertilizer use are explored more formally in the next section.

Table 8.2. Intensity of inorganic fertilizer use by major crops, Central highlands of Ethiopia, 2003.

Indicator of use	Agro-ecology					
	Upper highlands (N=1099)			Mid highlands (N=312)		
	Wheat	Barley	Tef	Wheat	Barley	Tef
Plots cultivated (No.)	244	323	1	37	4	117
Plots cultivated (%)	22.2	29.4	-	11.9	1.3	37.5
Mean plot size (ha)	0.28	0.38	-	0.39	0.24	0.65
Plots fertilized (%)	27.9	26.6	0.0	94.6	25.0	91.5
Average rate of use (kg/fertilized ha)	126.7	99.7	50	136.8	69.4	109.6
Average rate of use (kg/cropped ha)	35.3	27.2	-	129.4	17.4	100.3

Source: Farmers' survey

8.2.2 Empirical results of the multinomial soil fertility adoption model

This section presents the empirical results of the MNL soil fertility adoption model. The MNL model as specified in chapter seven with eight SFM options were used to test the

[30] Inorganic fertilizer recommendations for the major crops evolved from a blanket recommendation of 100 kg/ha of DAP for the major cereals to area specific recommendations. Currently, the nation-wide extension package program recommends the use of 100 kg/ha of DAP and 100 kg/ha of Urea for the major cereals.

validity of the independence of irrelevant alternatives (IIA) assumption. Parameter estimates from the initial run, although, had the expected sign failed to meet the IIA assumption. The model was thus restructured (redefined) following the suggestions of Heinrich and Wenger (2002) by collapsing closely related options into the same category. A close examination of the data revealed that within the choice set available to households, fallow and legume rotations were closely related. It has been noted in the previous chapter that smallholder farmers consider fallow and legume rotations as investments in soil fertility improvements with two years of maturity. A household's decision to use either a fallow or legume rotation on a given plot in the current year involves weighing foregone output against anticipated productivity gains in the second year from implementing the practices this year. Hence it was found appropriate to aggregate fallow and legume rotations into one category and animal manure use after fallow and legume rotations into another category reducing considered options from eight to six. Accordingly, the choice set in the restructured MNL model included the following soil fertility management options:

i. Fallow/legume rotations (SF/LR)
ii. Animal manure (AM) alone
iii. Animal manure in association with either SF or LR
iv. Inorganic fertilizer (IGF) alone
v. Inorganic fertilizer in association with SF, LR or AM (hence forth referred to as integrated soil fertility management)
vi. Continuous cropping without any soil fertility practice (no adoption)

The MNL model with these restructuring were then run and tested for the IIA assumption using a seemingly unrelated post-estimation procedure (SUEST)[31]. The test failed to reject the null hypothesis of independence of the included soil fertility management options suggesting there is no evidence against the correct specification of the MNL model for the soil fertility management practices (χ^2 value ranged from 8.6 to 16.9 with a

[31] SUEST is a generalization of the classical Hausman specification test useful for intra-model and cross-model hypotheses tests (StataCorp, 2003).

P value of 0.19 to 0.84). Therefore, the application of the MNL specification to the data set for modeling soil fertility adoption behavior of smallholder farmers is justified.

Table 8.3 presents the marginal effects along with the level of significance while the estimated coefficients are provided in Appendix VII. The likelihood ratio statistics as indicated by the χ^2 statistics is highly significant (P<0.00001) suggesting strong explanatory power of the model. The marginal effects measure the expected change in probability of a particular choice being made with respect to a unit change in an independent variable (Long, 1997; Green, 2000). In the MNL model, the marginal probabilities resulting from a unit change in an independent variable sum to zero since expected increases in marginal probabilities for a certain option induces a concomitant decrease for the other option(s) within the choice set. Noteworthy is that the interpretation of the marginal effects are dependent on the units of measurement of the independent variables. For instance a unit increase in the number of years of schooling of an average farmer would result in a 0.6% and 1.4% increase in the probability of using animal manure and integrated[32] soil fertility management (ISFM) practices. In all cases the estimated coefficients should be compared with the base category of not adopting any of the SFM practices (continuous cropping without soil fertility amendment practices).

Of household characteristics considered, education level of the head of a household is found to have a positive impact on the likelihood of using animal manure and ISFM practices. These results suggest that farmers with some level of formal education are well aware of the soil degradation problem and the synergetic effects of using multiple sources of plant nutrients. Hence, public interventions aimed at improving farmers' access to formal education are likely to improve the likelihood of using ISFM practices among smallholder farmers in the study area.

[32] Integrated soil fertility management refers to the combined use of inorganic and organic nutrient sources on the same plot of land.

Number of livestock owned, measured in TLU showed a positive and significant influence on the use of inorganic fertilizers alone or in association with traditional practices. Livestock is a source of traction, manure, cash and cushion against crop failures and other misfortunes. Households who own livestock are thus more likely to adopt ISFM practices and/or use multiple sources of nutrients as these households could get manure from their livestock and as the same time finance purchases of inorganic fertilizers from income generated from livestock products. The greater likelihood of using ISFM practices, therefore, could be due to the fact that respondents owning livestock are relatively better off, have got the resources and management skills, and are able to take the production and marketing risks associated with using inorganic fertilizers.

The institutional variables considered in the study were access to extension services, institutional credit for the purchase of inorganic fertilizers and off-farm income earning activities as well as land ownership (all measured as binary variables). As expected, access to extension services was positively and significantly associated with the use of animal manure, inorganic fertilizer alone or in association with traditional practices. Other things being equal, the chance of using ISFM on a typical plot would be higher by 12.5% for a households having access to extension services. However, the likelihood of using fallow/legume rotations reduces by 10.1% for a household having access to extension. These results suggest that households who have links with extension personnel are likely to switch to more intensive forms of production. It appears that extension messages emphasizing the complementary role of inorganic fertilizers with traditional practices (ISFM and multiple sources of nutrients) supported by practical demonstrations may stand a higher chance of success. These results, therefore, suggest an important role of increased institutional support to promote diffusion of knowledge regarding integrated soil fertility management.

Access to credit for the purchase of inorganic fertilizers found to have a significant positive impact on the likelihood of using inorganic fertilizers with and without traditional practices. On the other hand, the likelihood of using animal manure in association with fallow/legume rotations on a typical plot drops by 2.7% for a household having access to credit. This negative impact might be attributed to the fact that access to credit and hence access to inorganic fertilizers allows farmers to switch to more productive cereals. The positive marginal impact of credit access on adoption of ISFM practices could be explained by the marginal productivity of inorganic fertilizers when used after fallow/legume rotations or combined with animal manure. The results, therefore, suggest improving smallholder farmers access to institutional credit coupled with extension services would play an important role in raising the likelihood of inorganic fertilizer adoption as singly or in combination with other soil fertility management practices.

The dummy variable representing land ownership (PA[33] allotted plots as opposed to land leased in through informal land markets) showed a significant positive impact on the likelihood of using animal manure and ISFM practice. On the other hand the chances of using inorganic fertilizers alone on less secure (leased in plots through the informal land markets) would be higher by 5.0% compared to PA allotted plots that carry relatively better security. A possible explanation, other things being equal, farmers lacking legally defensible use rights prefer to use inorganic fertilizers on leased in land in an attempt to maximize short term benefits and save available manure to be used on relatively secure PA allotted plots. Therefore, the results support the contention that households engage in SFM practices that have a long-term nature such as animal manure on owned plots but use short term SFM practice (inorganic fertilizers) on leased in plots obtained through informal mechanisms. In a study of the impact of land tenure contracts on production efficiency in the highlands of Ethiopia, Gavian and Ehui (1999) found smallholder farmers use relatively higher amounts of chemical inputs (mainly commercial fertilizers) on less secure, non-PA allocated lands compared on relatively secure PA allotted plots. This result, therefore, support the hypothesis that the effect of land ownership on the adoption decision depends on the type of soil fertility management technology considered.

[33] PA allotted plots refers to those parcels of land allocated by PA officials directly to households for own cultivation.

Another factor hypothesized to influence the adoption decision was access to off-farm activity. Although access to off-farm activity was positively associated with all types of SFM practices but animal manure its impact was not statistically significant. This weak relationship might be attributed to the limited off-farm job opportunities available in the study area. Only 24.9% of the sample households were gainfully employed in various types of off-farm activities during the study year. A major criterion used for assessing a household's credit worthiness for the purchase of inputs such as commercial fertilizers, improved seeds and herbicides in the study area was ability to pay 10% of the cost of the input as a down payment. Therefore, expanding smallholder farmers access to off-farm cash earning activities is likely to raise inorganic fertilizer use by improving its credit worthiness.

It is widely believed that individual perceptions of plot characteristics and knowledge of site specific conditions influence the adoption decision of smallholder farmers in the study area. As expected, plot size positively and significantly influenced the likelihood of adopting all types of soil fertility management practices with the exception of the use of animal manure. Large plots are more convenient to work with and provide better returns to investments, as transaction costs per unit area are lower for larger plots than small plots. On the other hand, given the scarcity of manure due to limited herd size and its alternative use as a source of domestic fuel and cash sources, available manure resource would be efficiently used on smaller plots.

Number of plots owned by a household would have the effect of raising the likelihood of using fallow/legume rotations and ISFM practice. More plots mean larger farm size and hence making fallow/legume rotations more attractive than manure or inorganic fertilizers. Similarly, plot distance is negatively and significantly related with the use of animal manure alone or in combination with fallow/legume rotations. The use of manure involves extra costs for hauling and distributing manure to distant plots. Plots located near residences (backyard or a short distance from residences) are easy to manage, monitor and guard harvests as transaction costs are inversely related with distance. The negative association of plot distance with the likelihood of using animal manure thus confirms the empirical observations that transaction costs incurred for transporting and distributing manure are higher, the further the location of a field from a homestead. Most importantly, being attached to farmers' residences or a short distance thereof, such plots are low risk investments as the chance of loosing them is minimal in the event of land redistribution. The above results, therefore, suggest that land consolidation (fewer but larger plots located within a reasonable distance from households residence), might have a positive impact on adoption of manure that have a long term impact on soil fertility and crop productivity. Any land consolidation attempt, however, need to weigh the trade offs between increased benefits arising from reduced transaction costs with the potential losses that would be incurred from not having spatially scattered heterogeneous plots of land of various soil quality.

A household's perception of soil degradation measured as dichotomous variables indicating severity of degradation (sever, medium, light and none) and intensity of animal manure use in the recent past (whether a plot is rich in organic residues locally referred as "kossi" or "areda") significantly influenced the differential use of most of the SFM options. The likelihood of using manure by a household on a plot that received fortuitous manure in previous years (last five years) would be higher by 28.8% compared to a plot that did not receive manure in the recent past. Likewise, the chance of using inorganic fertilizers alone or combined with a traditional practice is higher on plots perceived to have some degree of physical degradation compared to the base category of no physical degradation. Given that distance of a plot is negatively related with the likelihood of using animal manure and that current use of animal manure is significantly associated with past use suggests that adoption of animal manure is mainly a function of transaction costs. Hence, measures that reduce transaction costs involved with hauling and distributing manure to distant fields would help improve the efficiency of resource use. The use of animal manure singly or in combination with other practices, however, appears not to be influenced by the degree of soil degradation of a plot.

As expected, agro-ecology turned out to be an important factor conditioning the differential use of SFM practices in the study area. The likelihood of using multiple sources of nutrients for an average farmer in the upper highlands appears to be higher compared to a similar farmer in the mid highlands. On the other hand, the chances of using inorganic fertilizer alone on a plot of average soil quality in the upper highlands is lower by 24.2% compared to a similar plot in the mid highlands. These findings confirm the hypothesis that inorganic fertilizers use is higher in the mid highlands where higher value crops, tef and wheat are well adapted and where crop responses to inorganic fertilizers are generally better due to the favourable climate. The finding that household in the upper highlands are more likely to adopt traditional SFM practices further confirm the hypothesis that traditional soil fertility management practices are better suited in the upper highlands where intensive and continuous crop cultivation is less attractive compared to the warmer mid highlands, and where smallholder farmers keep relatively larger number of livestock and own larger farm sizes than their counterparts in the mid highlands. This result suggests that future soil fertility management research and promotion programmes in the highlands need to clearly take into account agro-ecological variations.

Table 8.3. Marginal effects from the multinomial logit soil fertility adoption model, Central highlands of Ethiopia, 2003

Explanatory Variable	Seasonal fallowing (SF) or Crop rotations (LG)		Animal manure (AM) alone		Animal manure associated with either SF or LR		Inorganic fertilizers (IGF) alone		Inorganic fertilizer associated with either SF, LR or MR (ISFM)		No soil fertility management	
	Marginal effects	Sig. level	Marginal effects	Sig. level	Marginal effects	Sig. level	Marginal effects	Sig. level	Marginal effects	Sig. level	Marginal effects	Sig. level
Education[1]	-0.0050	0.421	0.0062*	0.089	0.0014	0.404	-0.0010	0.760	0.0142**	0.013	-0.0158*	0.054
Off-farm[2] income	0.0023	0.951	-0.0252	0.204	-0.0092	0.412	0.0275	0.314	0.0482	0.204	-0.0437	0.304
Livestock[3]	-0.0103**	0.022	0.0010	0.616	-0.0002	0.892	0.0035	0.144	0.0121***	0.001	-0.0061	0.231
Plot size[4]	0.2852***	0.000	-0.1293**	0.011	0.0033	0.895	0.0975***	0.000	0.2264***	0.000	-0.4832***	0.000
No. of plots	0.0219***	0.004	-0.0085**	0.024	-0.0022	0.288	0.0016	0.742	-0.0234***	0.000	0.0106	0.180
Plot distant[5]	0.0041***	0.000	-0.0091***	0.000	-0.0033***	0.000	0.0007	0.118	0.0029***	0.000	0.0047***	0.000
Severity of soil degradation[6]												
Light	-0.0957***	0.009	0.0457**	0.048	0.0580**	0.032	0.0422*	0.061	0.0185	0.622	-0.0687*	0.058
Medium	-0.0865**	0.026	-0.0013	0.947	0.0355	0.192	0.0429	0.102	0.0671*	0.077	-0.0576	0.186
Sever	-0.0172	0.727	-0.0334	0.178	0.0200	0.402	0.0596	0.165	0.0750*	0.081	-0.1040**	0.021
Tenure[7]	-0.0378	0.305	0.0735***	0.002	0.0163	0.158	-0.0495*	0.077	0.0599**	0.037	-0.0625	0.119
Credit[8]	-0.0432	0.278	-0.0198	0.308	-0.0265**	0.049	0.0461**	0.025	0.2465***	0.000	-0.2031***	0.000
Extension[9]	-0.1012**	0.009	-0.0118	0.724	0.0267	0.381	0.0679	0.173	0.1246*	0.056	-0.1061	0.159
Agro-ecology[10]	0.4212***	0.000	0.0172	0.305	0.0219*	0.068	-0.2422***	0.000	0.0379	0.136	-0.2560***	0.000
Kossi[11]	-0.2261***	0.000	0.2878***	0.002	0.0034	0.881	-0.0350*	0.073	-0.0675*	0.060	0.0374	0.707

***, **, *= Significant at 1%, 5% and 10% probability level, respectively;

[1]Number of years; [2]Dummy variable, 1 denoting participation in off-activities; [3]Tropical Livestock Unit (TLU); [4]hectares; [5]Minutes walked from residence; [6]comparison category is plots perceived not having shown any form of soil degradation; [7]dummy variable, 1 denoting PA allotted plots, 0 otherwise; [8]dummy variable, 1 denoting access to institutional credit; [9]dummy variable, 1 representing access to government extension; [10]dummy variable, 1 referring to upper highlands; [11]dummy variable with 1 indicating plot is reach in organic matter due to repeated manure application.

8.2.3 Results of the two-step Heckman model of adoption of inorganic fertilizers

This section presents empirical results of Heckman's two-step model determining the likelihood as well as intensity of inorganic fertilizer use among smallholder farmers in the Ethiopian highlands. While the dependent variable for the selection equation is binary indicating whether or not inorganic fertilizer was used on the plot in question, the dependent variable for the outcome equation is amount of inorganic fertilizer measured as the sum of DAP and Urea fertilizers in kilogram per hectare (kg/ha). The explanatory variables, besides those discussed in the previous section, include dummy variables representing soil fertility management practices used on the same plot the previous season (fallow rotation, legume rotation or farmyard manure) and an iteraction variable of district by use of stone/soil bunds.

As noted in chapter 7, one concern with the application of the Tobit specification is whether or not it adequately fits the data. The appropriateness of the Tobit model was tested using equation (7.12) by first estimating a probit, Tobit and truncated regression models with the same explanatory variables separately and then comparing the log-likelihood statistics of the Tobit model to the sum of the probit and truncated regression models. The loge-likelihood ratio (LR) test is highly significant (LR $\chi^2 = 259.20$ with P<0.0000) suggesting not only the presence of sample selection problem but also different set of variables are likely to influence the adoption decision and intensity of use of inorganic fertilizer use. The sample selection problem for the data set, however, does not require truncated regression for data exists for non-adopters. Hence, in what follows, results form the two-step Heckman model, which corrects for self-selection and assumes different set of variables influence the adoption decision and intensity of inorganic fertilizer use are presented and discussed. Noenethelless, given that most empirical studies use Tobit to estimate intensity of adoption and that the Tobit model allows estimation and decomposition of marginal effects, results from the Tobit model are presented in Appendix IX, for comparison purposes.

Table 8.4 presents Heckman's two-step model coefficient estimates (for the selection and outcome equations) and marginal probabilities for the selection equation. The likelihood function of the two-step Heckman model was significant (Wald $\chi^2 = 335.99$ with P<0.0000) showing a strong explanatory power. Also, the coffiecint of the mills lambda was significant (P<0.0000) providing evidence the presence of self-selection and hence justifaying the use of Heckman's two-step procedure.

As shown in Table 8.4, all hypothesized variables but land tenure and fallowing significantly influenced the likelihood of using inorganic fertilizers. On the other hand only a sub set of the hypothesized variables had a significant influence on intensity of inorganic fertilizer use. Variables significantly influenced intensity of inorganic fertilizer use includes education, livestock, number of plots owned, land tenure, access to credit and extension, agro-ecology and manure use.

As expected, education of the head of the household positively and significantly influenced both the likelihood of adoption and intensity of inorganic fertilizer use. A unit increase in the number of years of formal schooling of the head of a household will have the impact of raising the probability of using inorganic fertilizer by 1.5%. Likewise, heard size positively and significantly associated with both the probability and intensity of commercial fertilizer use. A unit increase in heard size would lead to an increase in the likelihood of commercial fertilizer use by 1.7%. The results, therefore, suggest that institutional interventions targeted at expanding access to education as well as improving herd size (e.g. improving access to veterinary services and credit) will have a positive impact on raising adoption and expected use of inorganic fertilizers in the study area.

Of the considered plot and farm characteristics, plot size, plot distance and perception of land degradation had a significant positive impact whereas number of plots owned negatively and significantly influenced adoption of inorganic fertilizer use. Other things being constant, the chances of using inorganic fertilizers on plots showing severe, medium and light degradation would be higher by 9.6%, 10.1% and 6.4%, respectively, compared to a plot perceived to be free from soil degradation. On the other hand, only number of plots owned had a significant influence on intensity of inorganic fertilizer. The negative marginal impact of number of plots might be explained by the high transaction costs and management inconveniences associated with managing a number of micro-plots scattered in a highly difficult terrain in the highlands. These results, therefore, call for land consolidation that allows households to have access to fewer but larger plots within the context of exploiting the diverse microclimates and heterogeneous land quality, a highly valued management strategy that allows households to exploit unique microenvironments and reduce climatic uncertainties.

Access to credit and extension showed positive and significant impact on both the adoption decision and use intensities. All else constant, the chances of using inorganic fertilizers on an average plot would be higher by 22.2% and 18.9% for households having access to extension and institutional credit for the purchase of inorganic fertilizers, respectively. Controlling for other factors, the type of land ownership, although, did not have significant association with the adoption decision; it positively and significantly influenced expected use. The results, therefore, suggest that making agricultural credit available coupled with technical support form extension have a high potential for raising both number of farmers using inorganic fertilizers and expected use rates among those currently using. Furthermore, reorienting extension efforts from the current method of prescribing blanket recommendation to providing information that empowers smallholder farmers to correctly diagnose soil degradation problems appears to have a high dividend.

The likelihood of using inorganic fertilizer increased for plots, which were put to fallow the previous year (chiflik plot) but reduced for plots that had either manure or were under legume rotations. Intensity of inorganic fertilizer, however, was only affected by manure use. Hence, it appears that smallholder farmers consider seasonal fallowing as a complementary soil fertility management practice whereas animal manure and legume rotations as a substitute input to inorganic fertilizers.

Another important result is that the dummy variable district (proxy for unobservable factors such as climatic variations, traditional values, attitudes and aspirations of the community) had a significant negative impact on the likelihood of using fertilizers. Other things being equal, the chances of using inorganic fertilizers on a typeical plot in Debre Birehan district would be lower by 23.9% compared to a similar plot in Dendi woreda. The differential impact of district on the likelihood of adoption could be explained by the relative agricultural potential of the two districts. While Dendi district is considered to be a high potential area with assured rainfall, the

Debre Birehan districted is a low potential area often experiencing crop failures arising from rainfall variability. On the other hand, the interaction variable, district by stone/soil bund use positively and significantly related to intensity of inorganic fertilizer suggesting that intenisity of fertilzer use is higher in Debre Birehan district on plots that had stone/soil bunds compared to plots that did not have stone/soil bunds. The positive impact of this interaction variable might be explained by the higher productivity and lower risk of using higher rates of inorganic fertilizers on plots that benefited from stone/soil bund investments. Also, intensity of use of inorganic fertilizers on a typical plot would be lower in the upper highlands compared to a similar plot in the mid-highlands. These results, therefore, suggest that different policy options could be pursued depending on whether the objective is to raise the number of farmers adopting inorganic fertilizers or increasing the intensity of use among household who are already using inorganic fertilizers. Information on the agro-ecology of an area coupled with knowledge of plot characteristics are important in predicting adoption rates, use intensities and could be valuable in fine-tuning inorganic fertilizer recommendations and marketing of inorganic fertilizers.

Table 8.4. Parameter estimates of Heckman's two-step model for the likelihood of adoption and intensity of inorganic fertilizer use (kg/ha), Central highlands of Ethiopia

	Probability of Adoption				Intensity of Use	
Variable	Coefficient	P-level	Marginal impact	P-level	Coefficient	P-level
Constant	-1.2343***	0.000			31.4010	0.358
Education[1]	0.0586***	0.004	0.0148***	0.0050	8.5763***	0.000
Off-farm income[2]	0.2970**	0.015	0.0860**	0.0150	-0.3603	0.971
Livestock[3]	0.0631***	0.000	0.0165***	0.0000	2.4061**	0.026
Plot size[4]	1.0600***	0.000	0.2669***	0.0000	-9.0019	0.535
No. of plots	-0.0415*	0.090	-0.0116*	0.0650	-5.8926***	0.006
Plot distant[5]	0.0051*	0.053	0.0013**	0.0470	0.0233	0.907
Severity of soil degradation[6]						
Light	0.2430**	0.046	0.0637*	0.0620	-1.5810	0.866
Medium	0.3683***	0.003	0.1017***	0.0080	8.0128	0.427
Sever	0.3468**	0.025	0.0963*	0.0490	17.2799	0.139
Tenure[7]	0.0325	0.799	0.0055	0.8660	20.9019**	0.019
Credit[8]	0.6636***	0.000	0.1885***	0.0000	35.3667**	0.010
Extension[9]	0.6955***	0.000	0.2217***	0.0000	29.8606**	0.038
Agro-ecology[10]	N.A	N.A	N.A	N.A	-27.8721***	0.004
District[11]	-0.8816***	0.000	-0.2385***	0.0000	N.A	N.A
SWC*District[12]	N.A	N.A	N.A	N.A	24.5376**	0.015
SFM used previous year[13]						
Legume rotations	-0.2388**	0.039	-0.0624**	0.0360	-3.2842	0.723
Manure	-1.0732***	0.000	-0.2160***	0.0000	-90.2482***	0.000
Fallow	0.1604	0.262	0.0481	0.2390	17.7982	0.108
Diagnostics						
Total observations	1293					
Censored	345					
Uncensored	948					
Mills lambda	68.3903***					
Wald Chi Square	335.3900***					

***, **, *= Significant at 1%, 5% and 10% probability levels, respectively; N.A=not applicable;
[1]Number of years; [2]Dummy variable, 1 denoting participation in off-activities; [3]Tropical Livestock Unit (TLU); [4]hectares; [5]Minutes walked from residence; [6]comparison category is plots perceived not having shown any form of soil degradation; [7]dummy variable, 1 denoting PA allotted plots, 0 otherwise; [8]dummy variable, 1 denoting access to institutional credit; [9]dummy variable, 1 representing access to government extension; [10]dummy variable, 1 referring to upper highlands; [11]dummy variables with 1 indicating Debre Birehan district; [12] interaction dummy variable (stone/soil bund use by district) with 1 indicating plots with stone/soil bunds in Debre Berihan district; [13]dummy variables with 1 indicating use of the respective SFM practices.

8.3 Results of the econometric analyses of factors determining use of soil and water conservation practices

This section discusses the empirical results of factors determining soil conservation practices among smallholder farmers in the study area. As is done in the previous section, two regression equations, a MNL model for the discrete choice variable of soil conservation adoption and a Tobit for the continuous variable of intensity of stone/soil bunds is estimated. The Tobit model is aimed at examining the factors associated with the intensity of the widely used soil conservation practice (stone/soil bunds popularly known as terraces measured in meters per ha).

Soil conservation practices traditionally practiced and promoted by the various projects on cultivated lands in the highlands include traditional ditches (*boyi*), cut-off drains (*golenta*), stone and soil bunds, grass-strips and Fanya juu[34]. While the first three practices are traditional, grass-strips and Fanya juu represent soil conservation practices introduced by various SWC projects. The importance and intensity of use of these physical soil conservation structures, however, varied widely between districts. Traditional ditches (*boyi*), simple drainage furrows constructed manually or by the traditional oxen drawn plow for removing excess water from a plot, are used widely in both districts, agro-ecologies and landforms except in extreme sloping plots. The traditional ditches are largely considered as a production practice mainly designed to minimize water logging rather than a soil conservation practice. Unlike the traditional ditches, which are believed to be a production practice, cut-off drains and stone/soil bunds are well-recognized soil conservation practices in both districts. Cut-off drains are semi-permanent drainage ditches constructed around a plot or parcel to protect draining water from upslope fields to inundate a parcel. While cut-off drains are used in both districts the use of stone/soil bunds is restricted to Debre Birehan district, constructed on 42% (2.5% in reasonable condition and 39.4% in excellent shape) of the cultivated plots compared to 1.4% (0.24% in reasonable condition and 1.2 in good shape) in Dendi district (Table 8.5). Debre Birehan district, identified as one of the heavily degraded areas in the central highlands and one with a tradition of using soil conservation practices, received government assistance for constructing stone and soil bunds on individual and

[34] Fanya juu are stone/soil embankments with drainage ditch on the lower side.

communal holdings in the 1980's and 1990's. Interestingly, despite the widely held view that smallholder farmers remove much of the soil conservation practices constructed by public assistance only 7.7% and 16.3% of the plots, which had some type of soil conservation structures (3.9% and 3.7% of the total plots) in Debre Birehan and Dendi, respectively, were removed. Adoptions of grass strips were dismal due to its incompatibility with the land tenure system where stubble fields after harvest are considered as communal (open to all community members for grazing livestock). Fanya juu were also rejected for its alleged problem of aggravating water logging.

Table 8.5. Use of soil conservation practices by smallholder farmers on cultivated lands (% of plots treated), Central highlands of Ethiopia, 2003

Soil and water conservation practices	Debre Birehan (N=724)	Dendi (417)	Both districts combined (1141)
Not ever constructed	50.00	79.38	60.74
Cut off drains (golenta) only			
Removed	1.66	2.88	2.10
Reasonable condition	0.14	1.68	0.70
Excellent condition	4.14	14.15	7.80
Stone and soil bunds			
Removed	2.21	0.48	1.58
Reasonable condition	2.49	0.24	1.67
Excellent condition	39.36	1.20	25.42

Source: Farmer's survey

8.3.1 Empirical results of the multinomial soil conservation adoption model

The choice set considered in the MNL model includes: cut off drains (golenta) only, stone/soil bunds with or without cut-off drains and no adoption of soil and water conservation practices. Marginal probabilities from the MNL soil conservation model are presented in Tables 8.6

whereas the model coefficients are given in Appendix VIII. The likelihood ratio statistics was highly significant (P<0.001) suggesting strong explanatory power of the included regressors. The IIA test, shown in Equation (5) of chapter 7, was implemented restricting (omitting) the cut-off drains option. The corresponding test statistics was ($P > \chi^2 = 0.6324$) suggesting that there was not enough evidence to reject the null hypothesis of independence of irrelevant alternatives. Therefore, the application of the MNL specification to the data set for modeling soil conservation adoption behavior of smallholder farmers appears to be justified.

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Interestingly, none of the household, farm and plot characteristics were found to be associated with the likelihood of using cut-off drains among smallholder farmers. This could be due to the very nature of the technology itself. Cut-off drains constitute simple and inexpensive drainage ditches constructed around a boundary of a plot or crop field in order to protect the field from inundation by runoff from up-slope fields. Once, cut-off drains are in place, maintenance costs are negligible and cooperation among smallholder farmers is a norm than the exception. Therefore, location rather than socio-economic differences among smallholder farmers might explain observed differential adoption of cut-off drains in the study area.

Education, off farm income, plot slope, perception of severity of soil degradation and government assistance significantly associated with the likelihood and intensity of using stone/soil bunds in the MNL model. The effect of considered factors will be discussed in more detail in the next section.

8.3.2 Empirical results of the Tobit soil conservation adoption model

As is done in the previous section, the presence of sample selection problem and whether or not the same set of covariates influence the adoption decision and intensity of use is tested using equation (7.17) of chapter 7. The Wald test of independence of the selection and outcome equations (ρ=0, Wald $\chi^2 = 0.54$ and P<0.4641) was not significant. Hence, based on the Wald test, the proposition that the same explanatory variables influence both the adoption decision and intensity of use as well as the hypothesis that there is no sample selection problem are not rejected. Hence, in what follows, results form the classical Tobit model, which assumes the same set of covariates influence the adoption decision and intensity of use are presented and discussed.

As expected, education is positively and significantly correlated with the adoption and intensity of stone/soil bund use. Household heads with relatively better formal education are likely to foresee the productivity consequences of soil degradation and soil conservation. Providing access to formal education would therefore play a crucial role in the fight against soil degradation and its consequences on food insecurity and poverty in the highlands of Ethiopia.

Among the farm and plot characteristics, plot size and plot slope positively and significantly affect both the likelihood of adoption and intensity of use. Similarly, other things being equal the chances of constructing soil conservation structures would be higher by 12% for plots having a medium slope compared to plots on bottom lands. In their soil conservation adoption studies, Shiferaw and Holden (1998) in the central highlands and Bekele and Drake (2003) eastern highlands of Ethiopia reported a positive correlation between slope and likelihood of using soil conservation structures.

The results also indicated that type of land ownership (PA allotted land as opposed to plots acquired through informal transactions) significantly influence both the adoption decision and intensity of use of stone/soil bunds by smallholder farmers. Stone/soil bunds are long term investments the benefits of which are realized after several years of initial investment. It is therefore rational for a household to restrict soil conservation investments on own land (land allotted directly by a PA to a household) as opposed to land acquired through informal land markets. While a household has legally defensible rights on land allotted to a household by PA officials, thus enjoy the benefits of soil conservation investments at such a time when land redistribution is to be done in the area, plots acquired through informal mechanisms have to be surrendered to the legal owner at the end of each cropping season.

Number of livestock owned, a proxy for the wealth position of a household, positively and significantly conditioned the likelihood and intensity of stone/soil bunds. As argued in the previous section, livestock are sources of cash and security against climatic uncertainties.

Households with livestock, therefore, are in a better position to invest on soil conservation for they have the financial resources to pay for the extra labour required for initial investments as well as afford the short term yield declines likely from reduced plot size (due to area taken by stone/soil bunds).

Access to extension measured by the number of contacts a household head had with extension personnel was positively and significantly (10.3%) related with the likelihood of using stone/soil bunds. In Ethiopia, agricultural extension services provided by the MOA is the major source of information on agriculture and natural resource conservation. The results therefore confirm the hypothesized positive role extension would play in natural resource conservation in general and soil conservation in particular.

Surprisingly, access to institutional credit for the purchase of inorganic fertilizers had a negative and significant influence both on the likelihood of adoption and intensity of use. The results suggest that the chances of investing in permanent soil conservation structures drops by 11.5% for a new household having access to short-term institutional credit. Similarly, among those who are currently using soil conservation structures intensity of use would be lower by 12.7 meters/ha for an average farmer having access to institutional credit compared to a household who did not have access. A possible explanation is that households who have access to short term credit for the purchase of inorganic fertilizers are likely to use inorganic fertilizers to compensate for lost soil nutrients and hence postpone adoption of soil conservation practices. This and other studies have shown the importance of improving smallholder farmers' access to credit in enhancing the adoption of inorganic fertilizers. The current short-term credit schemes targeted at raising the number of households using inorganic fertilizers and intensity of inorganic fertilizer use per unit of cropped area would only help solve the short term treats of soil degradation (soil nutrient mining) but could have a detrimental effect on the sustainable use of soil resources as inorganic fertilizer use do not compensate soil lost due to water erosion.

As expected perception of the severity of soil degradation and government assistance for initial construction of soil conservation practices positively and significantly influence the use of stone/soil bunds. The chances of investing in soil conservation structures would be higher by

23.1% for a household receiving assistance compared to a household who did not receive such assistance. This result contradicts the widely held view that assistance programs for construction of soil conservation structures in Ethiopia were largely unsuccessful and that soil conservation structures constructed under assistance programs were partially or wholly removed (Shiferaw and Holden, 1998). The result however, is consistent with the findings of Bekele and Drake (2003) who focused on the soil conservation research project (SCRP) site whereas our study areas are located outside the SCRP sites, and hence are broadly representative. Similarly, the chances of investing in soil conservation structures on plots displayed some degree of degradation would be higher by at least 14% compared to plots perceived to be free from any symptom of physical degradation.

Another important result noteworthy is that district (proxy for unobservable factors such as traditional values, attitudes and aspirations of the community) positively and significantly influenced the likelihood and intensity of investment in soil conservation structures. The chances of investing in soil conservation structures would be higher by 14.7% for a household in the Debre Birehan district compared to a similar household in Dendi. This could be explained by the relative extension efforts exerted in the two districts and local tradition. Smallholder farmers in Debre Birehan are well informed of the soil degradation problem and have a tradition of using stone and soil conservation structures. A number of soil conservation projects were also implemented by government and NGOs, which helped improve awareness and contributed to actual construction of soil conservation structures. In the Dendi district, however, extension efforts concentrated on extending improved crop packages consisting of improved crop varieties, agronomic practices and recommended type and rate of inorganic fertilizers. Group discussions with farmers in both districts revealed that for households in Dendi district soil degradation is tantamount to soil fertility decline while households in Debre Birehan stressed both dimensions of soil degradation, low soil fertility and soil physical degradation due to water erosion. This finding, therefore, suggest that use of soil conservation serves a different long –term purpose of reducing the long-term effects of soil degradation (irreversible aspect of soil degradation) whereas the use of inorganic fertilizer and integrated nutrient management only helps manage nutrient mining.

Table 8.6. Marginal effects of multinomial soil conservation adoption models, Central highlands of Ethiopia, 2003.

Variable	Cut-off drainage (golenta)		Stone, soil and raised boundary bunds			Non soil conservation (No adoption)
	Marginal effect	P-level	Marginal effect	P-level	Marginal effect	P-level
Education[1]	0.0035	0.465	0.0092**	0.039	-0.0127*	0.055
Off-farm income[2]	-0.0018	0.958	-0.0485***	0.010	0.0503	0.197
Livestock[3]	0.0055	0.164	-0.0014	0.555	-0.0041	0.394
Plot area[4]	-0.0284	0.214	0.0451	0.214	-0.0167	0.704
No. of plots	-0.0010	0.880	-0.0057	0.215	0.0067	0.394
Plot distance[5]	0.0007	0.251	-0.0003	0.553	-0.0004	0.564
Soil degradation[6]						
Sever	0.0714	0.248	0.4065***	0.000	-0.4779***	0.000
Medium	0.1356**	0.031	0.3671***	0.000	-0.5026***	0.000
Light	0.1333**	0.012	0.3254***	0.000	-0.4587***	0.000
Tenure[7]	0.0332	0.146	0.0229	0.271	-0.0562*	0.056
Credit[8]	-0.0479	0.178	-0.0300	0.257	0.0779*	0.095
Extension[9]	-0.0178	0.772	0.0310	0.587	-0.0133	0.881
Plot slope[10]	0.0061	0.750	0.1421***	0.000	-0.1483***	0.000
Assistance[11]	0.1393	0.343	0.3863**	0.012	-0.5257***	0.001
District[12]	-0.1450**	0.039	0.3172***	0.000	-0.1722**	0.035

***, **, *= Significant at 1%, 5% and 10% probability levels, respectively;
[1]Number of years; [2]Dummy variable, 1 denoting participation in off-farm activities; [3]Tropical Livestock Unit (TLU); [4]hectares; [5]Minutes walked from residence; [6]comparison category is plots perceived not having shown any form of soil degradation; [7]dummy variable, 1 denoting PA allotted plots; [8]dummy variable, 1 denoting access to institutional credit; [9]dummy variable, 1 representing access to government extension; [10]dummy variable, 1 representing plots on a higher slope (upland); [11]dummy variables, 1 denoting access to project assistance; [12]dummy variable, 1 referring to Debre Birehan district.

Table 8.7. Parameter estimates of the Tobit adoption model for the intensity of stone/soil bund use, Central highlands of Ethiopia, 2003

Variable	Coefficient	P-level	Adoption (index)		Expected use	
			Elasticity	Marginal effects	Elasticity	Marginal effects (m/ha)
Constant	-320.4803***	0.000				
Education[1]	6.0547*	0.068	0.0637*	0.0133**	0.0200**	1.4458**
Off-farm income[2]	-26.7276*	0.083	-0.0652*	-0.0567*	-0.0205*	-6.2248*
Livestock[3]	3.1450*	0.077	0.1650*	0.0069*	0.0518*	0.7510*
Plot area[4]	82.1367**	0.010	0.3153***	0.1798***	0.0989***	19.6137***
No. of plots	-3.5717	0.169	-0.1931	-0.0078	-0.0606	-0.8529
Plot distance[5]	0.0148	0.966	0.0022	0.0000	0.0007	0.0035
Soil degradation[6]						
Sever	127.4936***	0.000	0.1415***	0.3237***	0.0444***	37.7390***
Medium	158.7275***	0.000	0.2886***	0.3962***	0.0905***	47.1408***
Light	159.2407***	0.000	0.4400***	0.3802***	0.1380***	44.1137***
Tenure[7]	37.1450**	0.012	0.2769**	0.0763***	0.0869**	8.4359**
Credit[8]	-54.8909*	0.061	-0.1767*	-0.1153*	-0.0554*	-12.7187*
Extension[9]	43.1145	0.250	0.0231	0.1023	0.0072	11.1684
Plot slope[10]	54.7832***	0.000	0.2406***	0.1199***	0.0755***	13.1464***
Assistance[11]	91.7587***	0.001	0.0607***	0.2307***	0.0190***	26.0110***
District[12]	70.7553**	0.029	0.4032**	0.1470**	0.1265**	16.3012**
Diagnostics						
No. Observations	1141					
Wald Chi-Square	80.29***					

***, **, *= Significant at 1%, 5% and 10% probability levels, respectively;
[1]Number of years; [2]Dummy variable, 1 denoting participation in off-farm activities; [3]Tropical Livestock Unit (TLU); [4]hectares; [5]Minutes walked from residence; [6]comparison category is plots perceived not having shown any form of soil degradation; [7]dummy variable, 1 denoting PA allotted plots; [8]dummy variable, 1 denoting access to institutional credit; [9]dummy variable, 1 representing access to government extension; [10]dummy variable, 1 representing plots on a higher slope (upland); [11]dummy variable, 1 denoting access to project assistance; [12]dummy variable, 1 referring to Debre Birehan district.

8.4 Concluding summary

This chapter using plot level cross-sectional household survey data examined soil fertility management and soil conservation adoption behaviour of smallholder farmers in the Central Highlands of Ethiopia. Three sets of adoption models, a multinomial logit for the discrete dependent variables of soil fertility management and soil conservation practices involving multiple choices, Heckman's two-step and Tobit regression models for the continuous variables of inorganic fertilizers and stone/soil bund, respectively, were estimated. A number of important results of high policy significance were revealed.

First, the study showed the importance of farmer education in raising the likelihood of using most of the SFM practices as well as intensity of use of inorganic fertilizers and stone/soil bunds suggesting investment in education are indispensable to reducing soil degradation and improve farm income. Second, livestock a proxy for the wealth position of households, positively and significantly related with the likelihood of using inorganic fertilizers and ISFM practices. Livestock also has a positive and significant effect on the intensity of use of inorganic fertilizers and stone/soil bunds. Household with livestock (particularly oxen) not only use their land more productively but also leas in additional land from fellow farmers, take the production and marketing risks associated with using inorganic fertilizers and stone/soil bunds. Improving smallholder farmers' access to better livestock husbandry techniques particularly veterinary services coupled with measures that increases oxen ownership (individually or collaborative) would be vital to enhance adoption of soil fertility and conservation practices.

Third, project assistance in sharing the initial investment costs of SWC structures and access to extension are found to be important determinants of the intensity of SWC and inorganic fertilizers as well as the likelihood of using ISFM technologies suggesting government assistance is vital in improving adoption and hence contribute to more sustainable use of soil resources. Fourth, the likelihood of using manure, ISFM and stone/soil bunds is found to be significantly higher on owned lands than rented in or sharecropped plots suggesting improved tenure security is a precondition for households to engage in soil fertility management and soil conservation practices that have a long gestation period. Fifth, plot size and number of plots, a proxy for farm size, are positively and significantly related with the likelihood of using all types of SFM practices but animal manure suggesting land redistribution in the already degraded and land scarce highlands not only contribute to land fragmentation but also by raising the fixed costs of operating micro (very small) and dispersed plots further undermine sustainable farming and increase nutrient mining. Sixth, while access to institutional credit for the purchase of inorganic fertilizers enhanced both incidence and intensity of use of inorganic fertilizers it has a detrimental effect on the use of stone/soil bunds. This is an important tradeoff that should be considered seriously in policy formulation.

In view of the above findings the strategies to enhance both adoption and intensity of use of soil fertility and conservation practices in the highlands in general and the study area in particular need to focus on factors that showed higher marginal effects. Expanding formal education, improving smallholders' access to credit, extension services and off-farm income earning opportunities coupled with improving tenure security are vital policy requisites for raising adoption of soil fertility and conservation practices among smallholder farmers. Furthermore, government assistance in sharing the initial investment costs of soil conservation structures is likely to enhance adoption of soil conservation practices by smallholder farmers in the study area.

CHAPTER IX: SUMMARY, CONCLUSION AND IMPLICATIONS OF THE STUDY TO POLICY AND RESEARCH

Over the last three decades, agricultural production and income growth in Ethiopia lagged behind population growth. Consequently, per capita food production, income and savings have been falling. Disturbingly, in the highlands, soil, the basic natural resource on which the livelihood of the majority of the population is based has been progressively degraded. Excessive soil loss rates reaching over 100 tons/ha on croplands are not uncommon. Much worse, the amount of nutrients extracted from the soil through cropping is estimated to be several folds the nutrient inputs added to the soil in the form of organic and inorganic nutrients. Soil degradation due to water induced soil erosion and net nutrient extraction have thus become the major natural resource problem contributing to declining land productivity and food insecurity at household and national level.

In Ethiopia, past efforts to increase agricultural productivity, improve farm income, contain soil erosion and reverse soil nutrient mining are largely unsuccessful. Among others, biased development policies against smallholder farming, the institutional set up, population pressure, the biophysical environment, smallholder farmers' objectives and poor governance are thought to have contributed to declining land productivity, food insecurity and degradation of natural resource base.

First, development plans of the 1960's and 1970's focusing on industrialization and large-scale farming that could produce commodities for export or substitute imports denied the necessary supportive services required for improving the productivity of smallholder farming. Subsequent development plans recognized the vital role smallholder farming could play in reducing or closing the widening gap between food production and demand. However, assuming the country's food problem could be addressed through a quick fix of technological solutions, government and donor agencies adopted a technology transfer approach targeting few but high potential areas. Consequently, the vast majority of smallholder farmers producing for subsistence using traditional technologies on less favored areas with visible symptoms of soil degradation were neglected.

Second, the institutional set-up that perpetuated and accentuated land tenure insecurity hampered private investments in soil conservation and soil fertility enhancement. Third, the high population pressure characterizing the highlands of Ethiopia coupled with lack of alternative employment opportunities led to land fragmentation as the available land have been redistributed to the increasing population over generations. Land fragmentation exasperated by lack of suitable technologies to intensify farming forced farmers to either expand farming into marginal areas and/or mine the soil using traditional technologies that once were sustainable under low population pressure.

Fourth, soil degradation in the highlands of Ethiopia further worsened as smallholder farmers prompted by the need for securing adequate food for their family immediate needs continued to employ low-external input and erosive farming techniques which do not only mine the soil but also jeopardize the nations long-term food production ability. Last, but not least, lack of peace and security coupled with successive governments use of military power to deal with civil dissent and cross boundary conflicts not only undermined development efforts but also diverted scarce resources to support government war effort that would have been used otherwise.

Nevertheless, the notion that soil is a natural resource capital that could provide sustained flows of productive and environmental supporting services over time if managed properly appears to have received some recognition among the various stakeholders of agricultural development. Furthermore, the potential threat that soil degradation has posed on the income and welfare of smallholder farmers as well as on national food security is not disputed. However, the magnitude of the threat that soil degradation poses on current as well as future income to individual farmers and the national economy and how best to address the problem is not well known. Studies that estimate and model the economic costs of soil degradation are rare in Ethiopia. The few available studies employed static models, which do not account for the inter-temporal effects of changes in the soil capital (ignore the dynamic nature of the soil degradation and soil conservation investments). Furthermore, despite the fact that a large number of adoption studies had been carried out in Ethiopia to date, the attention provided to the analysis of soil conservation and soil nutrient management adoption behavior of smallholder farmers is minimal. Despite the fact that soil fertility management and conservation practices involve choices among several technological options the few available studies lumping the technological choices into two applied bi-variant models which did not consider information contained in interdependence and simultaneous adoption decision. This study, therefore, adopted a dynamic optimization framework in order to assess the inter-temporal trade-offs (the true social costs of soil loss relative to the value of output expected) that farmers face in their production decisions. It also analyzed the socio-economic factors that constrain adoption of soil fertility and soil conservation practices employing econometric models that account for simultaneity of choices.

The study was conducted in the highlands of Dendi and Debre Birehan Zuria in the Central Highlands of Ethiopia. The central highlands were chosen, as the area of focus for two reasons. First, the central highlands characterized by divers ecological aspects and settlement patterns represent the wider highlands of Ethiopia. Second, the central highlands provide a good contrast as soil fertility and soil conservation technologies were extensively promoted in some districts but not in others. The study, therefore, employed a multi-stage sampling procedure involving a purposive selection of regions, zones and districts followed by a random selection of peasant associations (PAs) within districts, and finally households from selected PAs. A total of 229 households managing some 1599 plots and sub plots were included in the study.

Necessary data were collected from various sources including secondary sources, participatory rural appraisal (PRA) and focused formal household surveys. Needed data at various scales (plot, farm and household) were collected. The collected data include plot characteristics (size, distance from residence, severity of soil degradation, fertility level, perceived plot productivity, slope), soil fertility and soil conservation practices used and production. Major socio-economic variables measured 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.

Both positive (econometric) and normative (optimization) analytical approaches were employed to achieve the stated objectives. First, recognizing that smallholder farmers manage several small plots of land scattered across micro-environments and that the nature of soil degradation facing farmers in low lying (bottom lands) is different from the soil degradation problem on sloping lands, the study developed two versions of an analytical dynamic control model for the respective soil degradation scenarios. The analytical optimal control model was then applied to the two soil degradation scenarios facing smallholder farmers in the Central highlands of Ethiopia to solve and compare optimal steady state solutions with profit maximizing static solutions and current farmer practices. Second, using plot level cross-sectional farm household survey, the study analysed the soil fertility and soil conservation adoption behaviour of smallholder farmers in the Central Highlands of Ethiopia. For the latter purpose, three sets of adoption models, multinomial logit for discrete dependent variables involving multiple choices, Heckman's two-step and Tobit regression models for the censored continuous dependent variables of intensity of inorganic fertilizers and stone/soil bund use, respectively, were estimated.

A comparison of the dynamic solutions at a socially desirable steady state with solutions of the static decision rule and current average practices revealed the following insights. First, the study showed that output under the dynamic decision rule for both soil degradation scenarios is much higher than the optimal output level under the static decision rule and current farmer practices suggesting there is a lot of room for improving the productivity of smallholder agriculture in the Central highlands of Ethiopia. Second, the optimal nutrient input required to attain and sustain steady state output under the dynamic decision rule is significantly higher than the requirements of the static decision rule and current farmer practices. Third, the optimal conservation effort required to attain and sustain steady state stock levels is much higher than current conservation efforts on both plot categories (bottom and upland plots). Fourth, 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. The above results lend themselves to the following conclusions:

- The static decision rule and current farmer practices are sub optimal compared to the socially desirable steady state dynamic solutions.

- Current soil fertility management and conservation practices are insufficient to curb the soil nutrient mining and physical degradation hazards and its ensuing problems of food insecurity and poverty facing smallholder farmers in the highlands of Ethiopia.

The reasons for the sub optimal use and extraction of the soil capital by smallholder farmers in the highlands of Ethiopia are believed to be associated with poverty, risk aversion behavior and land tenure insecurity, which force smallholder farmers to discount the future heavily. 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.

- The social gains from better utilization of soil resources (moving from current practice to the socially desirable steady state input and output levels) are tremendous.
- Despite the fact that current smallholder teff production practices are sub optimal compared to the desirable steady state dynamic solutions, the fact that current levels of inorganic N application and conservation efforts are higher than the static solutions suggest smallholder farmers consider some of the externalities of nutrient mining and soil physical degradation. Government assistance that unlocks the private incentives and help smallholder farmers adjust input 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.

A comparison of the dynamic solutions of scenario II with the nutrient mining scenario at a socially desirable steady state further revealed the following insights.

- Optimal steady state output under scenario II is significantly lower than the optimal output level under scenario I.
- Optimal levels of the control variables (labor, capital and inorganic N inputs) required to attain and sustain steady state output under scenario II are much lower than the respective input levels under the nutrient mining scenario suggesting the on-site effect of soil erosion (decline in SD) is to shift the production possibility frontier inwards.

- The net private and social gains under scenario II are considerably lower than the corresponding gains under scenario I suggesting failure to consider soil depth depletion under estimates costs or over estimates benefits.
- The optimal nutrient stock level for scenario II is lower than for scenario I suggesting soil quality and hence future productivity of the soil capital on uplands would be lower than on bottomlands.
- The optimal conservation effort required to achieve and sustain steady state stock levels (N and SD) under scenario II are higher by four folds over the requirements of the nutrient mining scenario highlighting the costs of soil erosion control on upland plots is significantly higher than on bottom plots.

The above results further 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. In 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. For instance on low lying plots where the overriding problem is net extraction of nutrients, the optimal mix of soil management practice is to raise current nutrient application rates to the steady state optimal level associated with modest levels of conservation effort. On slopping plots where both net nutrient extraction and soil erosion impinge on soil quality, sustainable utilization of the soil capital requires not only use of substantial levels of external nutrient inputs but also considerable investments in soil conservation effort. Nonetheless, given the high rate of time preference that smallholder farmers display, the lower average yields and that soil conservation investments are costly on slopping lands than on low laying plots it is unlikely that smallholder subsistence farmers take private initiatives to curb the alarming soil degradation prevalent on slopping lands. Government assistance such as input subsidies, credit provision, cost sharing arrangements for initial construction of conservation structures and well-taught and properly coordinated food-for-work programs would be indispensable to induce farmers invest in soil fertility and conservation practices that would have a long term desirable effect on the soil capital.

The sensitivity analysis showed that 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. Similarly a rise in output price and a fall in the price of N fertilizer would have the impact of raising steady state optimal input and output levels whereas a fall in output price and a rise in the price of inorganic N would have the opposite effect. Policies aimed 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 contribute to a more sustainable use of soil resources.

The econometric analysis of soil fertility and soil conservation adoption behaviour of smallholder farmers revealed strong evidence that the likelihood and intensity of using alternative SFM and conservation technologies by smallholder farmers on croplands are conditioned by different factors and at different levels of significance by the same factor. A number of findings of policy relevance have emerged from the analysis.

In both study districts, smallholder farmers have recognized soil degradation as a major problem responsible for the low and declining crop productivity and food insecurity prevalent in the study area. Nonetheless, households in Dendi district largely identified soil degradation with poor or declining soil fertility while households in Debre Birehan acknowledged both declining soil fertility (soil nutrient mining) and soil erosion to be equally important. Consequently, about three-quarters of the cultivated plots in both districts had received some type of soil fertility enhancement practice. Adoption of stone/soil bunds, however, was mainly restricted to the Debre Birehan district. This differential perception of soil degradation and adoption of soil degradation control practices among smallholder farmers have partly been reinforced and nurtured by the relative emphasis agricultural extension had placed and interventions implemented in the study areas. Despite the fact that soil degradation were apparent in both districts (more so in Debre Birehan), agricultural extension programs in Dendi districts, until recently, emphasized on increasing crop productivity through the promotion of extension packages consisting of improved crop varieties, recommended types and rates of inorganic fertilizers, optimum weed and pest control practices. On the other hand, in Debre Birehan district, besides the promotion of improved crop technologies, soil conservation had received considerable attention. Given that the probability and intensity of using most of the soil fertility management practices is positively related with access to extension and that government assistance is positively associated with the likelihood of using stone/soil bunds, continued extension assistance and government support is vital in the fight against soil degradation and its consequences of food insecurity and poverty.

The study revealed that ago-ecological variations have a differential impact on the adoption of soil fertility management practices among smallholder farmers. The use of multiple sources of nutrients on a single plot is wide spread in the upper highlands while inorganic fertilizers seem to be the major soil fertility management practice in the mid highlands where a high value crop, teff, is predominantly grown. Hence, future soil fertility management research and promotion programmes in the highlands need to clearly take into account agro-ecological variations. In the upper highlands where manure use and fallow rotations are common the possibility of improving the efficiency of available manure through composting and introducing improved fallowing practices need to be looked at.

Across all specifications, access to education was found to be associated with the likelihood of adoption of most of the soil fertility management and soil conservation practices as well as the intensity of use of inorganic fertilisers and stone/soil bunds. In a country where 60% of the adult population (over 15 years of age) is illiterate, improving smallholder farmers' access to formal education and improving skills through extension education in diagnosing soil degradation and other soil related problems would be effective in improving both the likelihood of adoption and intensity of use of inorganic fertilizers and soil/stone bunds (conservation).

Poverty in asset endowments was found to be an important determinant of adoption of inorganic fertilizers and stone/soil bunds suggesting the less endowed (the poorest of the poor) will be less likely to use commercial fertilizers and engage in soil conservation activities. Policies geared towards reducing poverty are thus likely to improve adoption of soil fertility management and soil conservation practices in the study areas. Furthermore, project assistance in sharing initial costs for constructing soil conservation structures form an important incentive for adoption of stone/soil bunds suggesting government assistance will be pivotal in improving rural income as well as contribute to reversing soil degradation. Well thought and properly coordinated external assistance by government and NGO's (e.g. food for work) is thus likely to play a positive role in containing soil degradation, improving productivity thereby reduce poverty.

On the other hand, access to short term credit is found to have contradictory effects on adoption. While access to short term credit for the purchase of inorganic fertilizer has a positive impact on both the likelihood of adoption and intensity of use of inorganic fertilizer, it had a negative and significant impact on the probability and intensity of use of stone/soil bunds suggesting that farmers having access to institutional credit do not see the need for soil conservation or postpone adoption of soil conservation. This result is consistent with the findings of Holden and Shiferaw (2004) in the Andit Tid area of North Shewa. Improving smallholder farmers' access to short-term credit for the purchase of inorganic fertilizers, therefore, needs to be designed cautiously taking into consideration its long-term effect on soil conservation adoption. Providing information on the likely danger of relying heavily on short term yield enhancing soil fertility management practices to deal with the soil degradation problem would be useful to improve awareness and help households make informed decisions.

Plot size is found to have a positive impact (except in case of manure use) both on adoption of soil fertility and conservation practices as well as intensity of stone/soil bund use. Further land redistribution in the already degraded and land scarce highlands, therefore, not only contribute to land fragmentation but also by raising the fixed costs of operating micro (very small) and dispersed plots further undermine sustainable farming and increase nutrient mining. Land consolidation that allows households to have access to fewer but larger plots within the context of exploiting the diverse microclimates and heterogeneous land quality is likely to improve adoption of soil fertility and conservation practices.

The likelihood of using manure, ISFM and stone/soil bunds is found to be significantly higher on owned lands than leased in plots suggesting that improved tenure security is a precondition for households to engage in soil fertility management and soil conservation practices that have a long gestation period. Improving tenure security is thus likely to enhance adoption of soil fertility and soil conservation practices that have a long-term nature.

This thesis provided analysis of the socio-economic aspects of soil degradation as it applies to smallholder farmers based on data collected from two districts in the Central highlands of Ethiopia. Results of the study therefore need to be viewed and interpreted with the following caveats in mind. First, although all effort had been made to select representative locations so that results have relevance to the wider highlands, care need be exercised when extrapolating results to other parts of the highlands where natural and socio-economic features are much different from the Central Highlands. Second, the study employed econometric (positve) models for analysing the determinants of adoption of soil mangement technologies among smallholder farmers and normative (optimization) analytical techniques for estimating the intertemporal effects of soil nutrient depletion and erosion. Although the analytical approaches adopted for the considered research problems as such were appropriate, the discrete nature of the approaches did not allow exploring the linkage between socio-economic variables determining soil management adoption and biophysical processes governing erosion and soil nutrient depletion. The challagne for future research, therefore, would be to search for an alalytical tool that would enable exploring more fully the linakages between socio-economic variables influcning technology choice and biophysical variables governing soil erosion and soil nutrient depeletion. Third, due to data limitations the study assumed only one crop, teff, is grown on the same piece of land and modelled the inter-temporal allocation of resources. In reality, however, in the highlands, crop rotation is a norm than the exception and hence future modelling exercises need to consider, besides the conventional production and conservation inputs, crop mix as a choice variable. Fourth, despite the fact that soil degradation has both on-site and off-site impacts imposing far-reaching consequences on the welfare of individual households and society at large, this study concentrating on on-site impacts did not attempt to capture the off-site impacts of soil degradation. It is therefore important that future studies explore off-site impacts of soil degradation on the welfare of individual households as well as society at large. Fifth, another important aspect that has not been dealt with and need consideration in future research concerning soil fertility management and conservation is the impact of risk on the adoption and resource allocation decisions of smallholder farmers. Sixth, the study relied heavily upon broadly representative secondary data (e.g. erosion rates) to empirically specify some components of the optimal control model and subsequently solve for the optimal values. Model results should, therefore, be interpreted in this light.

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APPENDICES

Appendix I. Current Value Hamiltonian version of the soil nutrient mining control problem

The current value Hamiltonian of the nutrient mining problem is given by:

$$\mathrm{H}_C(F, L_Y, L_S, K_Y, \eta) = Pf(L_Y, K_Y, N) - \left(W_F F + W_L L_Y + W_S L_S + W_K K_Y\right)$$
$$+ \eta[G(F) - D(Y) + M(Z, L_S, Y)] \qquad (1.1)$$

$$\text{Where: } \eta = e^{\delta t}\mu \qquad (1.2)$$

The FOC for this system:

$$\frac{\partial \mathrm{H}_C}{\partial F} = -W_F + \eta \frac{\partial G}{\partial F} = 0 \Rightarrow W_F = \eta G_F \qquad (1.3)$$

$$\frac{\partial \mathrm{H}_C}{\partial L_Y} = P\frac{\partial f}{\partial L_Y} - W_L - \eta \frac{\partial D}{\partial L_Y} + \eta \frac{\partial M}{\partial L_Y} = 0 \qquad (1.4)$$

$$\frac{\partial \mathrm{H}_C}{\partial K_Y} = P\frac{\partial f}{\partial K_Y} - W_K - \eta \frac{\partial D}{\partial K_Y} + \eta \frac{\partial M}{\partial K_Y} = 0 \qquad (1.5)$$

$$\frac{\partial \mathrm{H}_C}{\partial L_S} = -W_S + \eta \frac{\partial M}{\partial L_S} = 0 \qquad (1.6)$$

$$\dot{\eta} = \delta\eta - \frac{\partial \mathrm{H}_C}{\partial N} = \delta\eta - P\frac{\partial f}{\partial N} + \eta(\frac{\partial D}{\partial N} - \frac{\partial M}{\partial N}) \qquad (1.7)$$

$$\frac{\partial \mathrm{H}_c}{\partial \eta} = \dot{N} = G(F) - D(Y) + M(Z, L_S, Y) \qquad (1.8)$$

Assuming a steady state where $\dot{\eta} = \dot{N} = 0$, the first order conditions shown in equations (1.1 through 1.8) could be restated as follows:

$$\eta = \frac{W_F}{G_F} \tag{1.3b}$$

$$\eta = \frac{Pf_{L_Y} - W_L}{D_{L_Y} - M_{L_Y}} \tag{1.4b}$$

$$\eta = \frac{Pf_{K_Y} - W_K}{D_{K_Y} - M_{K_Y}} \tag{1.5b}$$

$$\eta = \frac{W_S}{M_{L_S}} \tag{1.6b}$$

$$\eta = \frac{Pf_N}{[(D_N - M_N) + \delta]} \tag{1.7b}$$

$$G(F) = D(Y) - M(Z, L_S, Y) \tag{1.8b}$$

Equation (1.8b) above states that at steady state, the net nutrient depletion through crop harvest, erosion and natural processes are matched by external nutrients added to the soil. Further combining equations 1.3b with each of 1.4b through 1.7b, the following equations are derived:

$$\frac{W_F}{G_F} = \frac{Pf_N}{[(D_N - M_N) + \delta]} \tag{1.9}$$

$$\frac{Pf_{L_Y} - W_L}{D_{L_Y} - M_{L_Y}} = \frac{Pf_N}{[(D_N - M_N) + \delta]} \tag{1.10}$$

$$\frac{Pf_{K_Y} - W_K}{D_{K_Y} - M_{K_Y}} = \frac{Pf_N}{[(D_N - M_N) + \delta]} \tag{1.11}$$

$$\frac{W_S}{M_{L_S}} = \frac{Pf_N}{[(D_N - M_N) + \delta]} \tag{1.12}$$

Eliminating, common terms the following fundamental equation is derived:

$$\eta = \frac{W_F}{G_F} = \frac{Pf_N}{[(D_N - M_N) + \delta]} = \frac{Pf_{L_Y} - W_L}{D_{L_Y} - M_{L_Y}} = \frac{Pf_{K_Y} - W_{K_Y}}{D_{K_Y} - M_{K_Y}} = \frac{W_{L_s}}{M_{L_s}} \tag{1.13}$$

Appendix II. Summary of specified functions and functional relationships used in the empirical soil degradation control model

The reduced form solutions of the control model for both scenarios (soil nutrient mining only) as well as (soil nutrient mining and physical soil degradation) are based on the following empirical specifications:

1. The production function:

$$Y = AL_Y^b K_Y{}^c SD^d N^g \qquad (2.1)$$

2. The aggregate soil regeneration and decay function (H)

   2.1. Relationship between soil conservation effort and erosion damage

$$E_t = \tau e^{\alpha L_S} \qquad (2.2)$$

   2.2. Contribution of canopy to soil decay

$$J = \phi(1 - e^{-vY}) \qquad (2.3)$$

Accordingly combinning equations (2.2 and 2.3), we have

$$h = E_t - J = \tau e^{-\alpha L_S} - \phi(1 - e^{-vY}) \qquad (2.4)$$

The natural rate of soil regeneration, Z, is constant. The aggregate soil regeneration and decay function, H (Z, L_S, Y) is given by

$$H = Z - h = Z - E + J$$

$$H = Z - \tau e^{-\alpha L_S} + \phi(1 - e^{-vY}) \qquad (2.5)$$

3. The nutrient regeneration and damage function

3.1. The nutrient augmentation function, G(F)

$$G(F) = \beta_1 F \tag{2.6}$$

3.2. Nutrient depletion due to biomass removal

$$D(Y) = \beta_2 Y \tag{2.7}$$

3.3. Nutrient regeneration and damage due to erosion and natural processes

$$M = \beta_3[Z - \tau e^{-\alpha L_S} + \phi(1 - e^{-\nu Y})] \tag{2.8}$$

Accordingly the aggregate nutrient regeneration and damage function is given by

$$N = G(F) - D(Y) + M(Z, L_S, Y) \tag{2.9}$$

$$N = \beta_1 F - \beta_2 Y + \beta_3[Z - \tau e^{-\alpha L_S} + \phi(1 - e^{-\nu Y})] \tag{2.10}$$

Reduced form solutions for the optimality conditions derived in appendices III, IV and V are based on the following functional relationships.

The production function is specified as:

$$f(L_Y, K_Y, SD, N) = Y = AL_Y^b K_Y^c SD^d N^g \tag{2.11}$$

Accordingly, the respective marginal products (partial derivatives with respect to its arguments) are given by:

$$\frac{\partial f}{\partial L_Y} = f_{L_Y} = bAL_Y^{b-1}K_Y^{c}SD^{d}N^{g} = \frac{bY}{L_Y} \qquad (2.12)$$

$$\frac{\partial f}{\partial K_Y} = f_{K_Y} = cAL_Y^{b}K_Y^{c-1}SD^{d}N^{g} = \frac{cY}{K_Y} \qquad (2.13)$$

$$\frac{\partial f}{\partial SD} = f_{SD} = dAL_Y^{b}K_Y^{c}SD^{d-1}N^{g} = \frac{dY}{SD} \qquad (2.14)$$

$$\frac{\partial f}{\partial N} = f_{N} = gAL_Y^{b}K_Y^{c}SD^{d}N^{g-1} = \frac{gY}{N} \qquad (2.15)$$

The respective partial derivatives of the soil regeneration and damage function are given by:

$$\frac{\partial H}{\partial L_Y} = H_{L_Y} = \phi v e^{-vY}\frac{\partial f}{\partial L_Y} = \varphi\frac{bY}{L_Y} \qquad (2.16)$$

Where: $\phi v e^{-vY} = \varphi$

$$\frac{\partial H}{\partial K_Y} = H_{K_Y} = \phi v e^{-vY}\frac{\partial f}{\partial K_Y} = \varphi\frac{cY}{K_Y} \qquad (2.17)$$

$$\frac{\partial H}{\partial SD} = H_{SD} = \phi v e^{-vY}\frac{\partial f}{\partial SD} = \varphi\frac{dY}{SD} \qquad (2.18)$$

$$\frac{\partial H}{\partial N} = H_{N} = \phi v e^{-vY}\frac{\partial f}{\partial N} = \varphi\frac{gY}{N} \qquad (2.19)$$

$$\frac{\partial H}{\partial L_S} = H_{L_S} = \tau\alpha e^{-\alpha L_S} \qquad (2.20)$$

Partial derivatives of the nutrient regeneration and damage function with respect to its arguments:

$$\frac{\partial M}{\partial L_Y} = M_{L_Y} = \beta_3 \phi v e^{-vY} \frac{\partial f}{\partial L_Y} = \beta_3 \varphi \frac{bY}{L_Y} \qquad (2.21)$$

$$\frac{\partial M}{\partial K_Y} = M_{K_Y} = \beta_3 \phi v e^{-vY} \frac{\partial f}{\partial K_Y} = \beta_3 \varphi \frac{cY}{K_Y} \qquad (2.22)$$

$$\frac{\partial M}{\partial SD} = M_{SD} = \beta_3 \phi v e^{-vY} \frac{\partial f}{\partial SD} = \beta_3 \varphi \frac{dY}{SD} \qquad (2.23)$$

$$\frac{\partial M}{\partial N} = M_N = \beta_3 \phi v e^{-vY} \frac{\partial f}{\partial N} = \beta_3 \varphi \frac{gY}{N} \qquad (2.24)$$

$$\frac{\partial M}{\partial L_S} = M_{L_S} = \beta_3 \tau \alpha e^{-\alpha L_s} \qquad (2.25)$$

Partial derivatives of the nutrient depletion function due to biomass removal, D(Y), with respect to its arguments:

$$\frac{\partial D}{\partial L_Y} = D_{L_Y} = \beta_2 \frac{\partial f}{\partial L_Y} = \beta_2 \frac{bY}{L_Y} \qquad (2.26)$$

$$\frac{\partial D}{\partial K_Y} = D_{K_Y} = \beta_2 \frac{\partial f}{\partial K_Y} = \beta_2 \frac{cY}{K_Y} \qquad (2.27)$$

$$\frac{\partial D}{\partial SD} = D_{SD} = \beta_2 \frac{\partial f}{\partial SD} = \beta_2 \frac{dY}{SD} \qquad (2.28)$$

$$\frac{\partial D}{\partial N} = D_N = \beta_2 \frac{\partial f}{\partial N} = \beta_2 \frac{gY}{N} \qquad (2.59)$$

Partial derivative of the nutrient augmentation function:

$$\frac{\partial G}{\partial F} = \beta_1 \qquad (2.30)$$

Accordingly,

$$\frac{H_N}{H_{L_Y}} = \frac{gL_Y}{bN} \tag{2.31}$$

$$\frac{H_N}{H_{K_Y}} = \frac{gK_Y}{cN} \tag{2.32}$$

$$\frac{H_N}{H_{L_s}} = \frac{\varphi g Y}{\tau \alpha e^{-\alpha L_S} N} \tag{2.33}$$

$$D_{L_Y} - M_{L_Y} = \frac{bY}{L_Y}\left(\beta_2 - \beta_3 \phi v e^{-vY}\right) = \frac{bY}{L_Y}\xi \tag{2.34}$$

Where: $\beta_2 - \beta_3 \phi v e^{-vY} = \xi$

$$D_{K_Y} - M_{K_Y} = \frac{cY}{K_Y}\left(\beta_2 - \beta_3 \phi v e^{-vY}\right) = \frac{cY}{K_Y}\xi \tag{2.35}$$

$$D_{SD} - M_{SD} = \frac{dY}{SD}\left(\beta_2 - \beta_3 \phi v e^{-vY}\right) = \frac{dY}{SD}\xi \tag{2.36}$$

$$D_N - M_N = \frac{gY}{N}\left(\beta_2 - \beta_3 \phi v e^{-vY}\right) = \frac{gY}{N}\xi \tag{2.37}$$

Given the above formulations, the optimal solutions derived from the first order conditions for the soil-mining scenario are specified below:

$$\frac{W_F}{G_F} = \frac{W_F}{\beta_1} \tag{2.38}$$

$$\frac{Pf_{L_Y} - W_L}{D_{L_Y} - M_{L_Y}} = \frac{PbY - W_L L_Y}{bY\xi} \tag{2.39}$$

$$\frac{Pf_{K_Y} - W_K}{D_{K_Y} - M_{K_Y}} = \frac{PcY - W_K K_Y}{cY\xi} \tag{2.40}$$

$$\frac{W_{L_S}}{M_{L_S}} = \frac{W_S}{\beta_3 \tau \alpha e^{-\alpha L_S}} \tag{2.41}$$

$$\frac{Pf_N}{[(D_N - M_N) + \delta]} = \frac{PgY}{gY\xi + \delta N} \tag{2.42}$$

$$G(F) = D(Y) - M(Z, L_S, Y) \Rightarrow \beta_1 F = \beta_2 Y - \beta_3 \left[Z - \tau e^{-\alpha L_S} + \phi(1 - e^{-vY})\right] \tag{2.43}$$

Appendix III. Derivation of the reduced form solutions for the choice variables (L_Y, L_S, K_Y and F) and the optimal nutrient stock (N) for the soil-mining scenario

Equating equation (2.39) with equation (2.40)

$$\frac{PbY - W_L L_Y}{bY\xi} = \frac{PcY - W_K K_Y}{cY\xi}$$

$$c\left(PbY - W_L L_Y\right) = b\left(PcY - W_K K_Y\right)$$

$$cW_L L_Y = bW_K K_Y$$

$$L_Y = \frac{bW_K K_Y}{cW_L} \tag{3.1a}$$

$$K_Y = \frac{cW_L L_Y}{bW_K} \tag{3.2a}$$

Equating equation (2.38) with equation (2.39) to solve for N and assuming $\beta_1 = 1$:

$$W_F = \frac{PbY - W_L L_Y}{bY\xi}$$

$$W_F bY\xi = PbY - W_L L_Y$$

$$W_L L_Y = PbY - W_F bY\xi$$

$$W_L L_Y = bY(P - W_F \xi)$$

$$\frac{bY}{W_L L_Y} = \frac{b(AL_Y^{b-1} K_Y^c N^{g})}{W_L} = \frac{1}{(P - W_F \xi)} \tag{3.3}$$

Substituting equation (3.2a) into equation (3.3):

$$\left(\frac{b}{W_L}\right)AL_Y^{b-1}\left(\frac{cW_L}{W_K b}\right)^c L_Y^c N^g = \frac{1}{(P-W_F\xi)}$$

$$AL_Y^{(b+c-1)}\left(\frac{b}{W_L}\right)^{1-c}\left(\frac{c}{W_K}\right)^c N^g = \frac{1}{(P-W_F\xi)}$$

$$L_Y = \left(\frac{b}{W_L}\right)^{\frac{c-1}{b+c-1}}\left(\frac{c}{W_K}\right)^{\frac{-c}{b+c-1}}\left(\frac{1}{AN^g(P-W_F\xi)}\right)^{\frac{1}{b+c-1}} \tag{3.1b}$$

Substituting equation (3.1b) back to equation (3.2a)

$$K_Y = \left(\frac{c}{W_K}\right)\left(\frac{b}{W_L}\right)^{-1}\left[\left(\frac{b}{W_L}\right)^{\frac{c-1}{b+c-1}}\left(\frac{c}{W_K}\right)^{\frac{-c}{b+c-1}}\left(\frac{1}{AN^g(P-W_F\xi)}\right)^{\frac{1}{b+c-1}}\right]$$

$$K_Y = \left(\frac{b}{W_L}\right)^{\frac{-b}{b+c-1}}\left(\frac{c}{W_K}\right)^{\frac{b-1}{b+c-1}}\left(\frac{1}{AN^g(P-W_F\xi)}\right)^{\frac{1}{b+c-1}} \tag{3.2b}$$

Equating equation (2.38) with equation (2.42) to solve for N:

$$W_F = \frac{PgY}{gY\xi + \delta N}$$

$$W_F gY\xi + W_F\delta N = PgY$$

$$W_F\delta N = PgY - W_F gY\xi$$

$$gY(P - W_F\xi) = W_F\delta N$$

$$\frac{Y}{N} = AL_Y^b K_Y^c N^{g-1} = \frac{W_F \delta}{g\left(P - W_F \xi\right)} \tag{3.4a}$$

Considering the LHS and substituting equations (3.1b and 3.2b)

$$AL_Y^b = A\left(\frac{b}{W_L}\right)^{\frac{bc-b}{b+c-1}}\left(\frac{c}{W_K}\right)^{\frac{-bc}{b+c-1}}\left(\frac{1}{AN^g\left(P - W_F\xi\right)}\right)^{\frac{b}{b+c-1}}$$

$$K_Y^c N^{g-1} = \left(\frac{b}{W_L}\right)^{\frac{-bc}{b+c-1}}\left(\frac{c}{W_K}\right)^{\frac{cb-c}{b+c-1}}\left(\frac{1}{AN^g(P - W_F\xi)}\right)^{\frac{c}{b+c-1}} N^{g-1}$$

Pulling the components of the LHS together and equating with the RHS

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

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

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

Let : $1 - g - c - b = \varpi$,

Accordingly, substituting the above expression and solving for N:

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

$$N^{*} = A^{\frac{1}{\varpi}} \left(\frac{c}{W_K} \right)^{\frac{c}{\varpi}} \left(\frac{b}{W_L} \right)^{\frac{b}{\varpi}} \left(\frac{W_F \delta}{g} \right)^{\frac{b+c-1}{\varpi}} \left(P - W_F \xi \right)^{\frac{1}{\varpi}} \tag{3.4b}$$

Substituting the values of N from equation (3.4b) into equation (3.1b) to solve for the optimal value of L_Y:

From equation (3.1b), we have

$$L_Y = \left(\frac{b}{W_L} \right)^{\frac{c-1}{b+c-1}} \left(\frac{c}{W_K} \right)^{\frac{-c}{b+c-1}} \left(\frac{1}{AN^{g}(P - W_F \xi)} \right)^{\frac{1}{b+c-1}}$$

Substituting equation (3.4b) to the above and solving for L_Y:

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

$$L_{Y}^{*} = A^{\frac{1}{\varpi}} \left(\frac{c}{W_K} \right)^{\frac{c}{\varpi}} \left(\frac{b}{W_L} \right)^{\frac{\varpi(c-1)-bg}{\varpi(b+c-1)}} \left(\frac{W_F \delta}{g} \right)^{\frac{-g}{\varpi}} \left(P - W_F \xi \right)^{\frac{1}{\varpi}} \tag{3.1c}$$

Substituting the values of N from equation (3.4b) to equation (3.2b) to solve for the optimal value of K_Y:

From equation (3.2b), we have

$$K_Y = \left(\frac{b}{W_L} \right)^{\frac{-b}{b+c-1}} \left(\frac{c}{W_K} \right)^{\frac{b-1}{b+c-1}} \left(\frac{1}{AN^{g}(P - W_F \xi)} \right)^{\frac{1}{b+c-1}}$$

Substituting equation (3.4b) to the above and solving for K_Y:

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

$$K_Y^* = A^{\frac{1}{\omega}} \left(\frac{c}{W_K}\right)^{\frac{\varpi(b-1)-cg}{\varpi(b+c-1)}} \left(\frac{b}{W_L}\right)^{\frac{b}{\varpi}} \left(\frac{W_F \delta}{g}\right)^{\frac{-g}{\varpi}} \left(P - W_F \xi\right)^{\frac{1}{\varpi}} \qquad (3.2c)$$

Equating equation (2.38) with equation (2.41) to solve for L_S:

$$W_F = \frac{W_S}{\beta_3 \tau \alpha e^{-\alpha L_S}}$$

$$W_F \beta_3 \tau \alpha e^{-\alpha L_S} = W_S$$

$$e^{-\alpha L_S} = \frac{W_S}{W_F \beta_3 \tau \alpha}$$

$$e^{\alpha L_S} = \frac{W_F \beta_3 \tau \alpha}{W_S}$$

$$\alpha L_S = \ln\left(\frac{W_F \beta_3 \tau \alpha}{W_S}\right)$$

$$L_S^* = \left(\frac{1}{\alpha}\right) \ln\left(\frac{W_F \beta_3 \tau \alpha}{W_S}\right) \qquad (3.5)$$

Given the optimal values for L_Y, K_Y and N above, the optimal output at a desirable steady state is given by:

$$Y^* = A L_Y^{*b} K_Y^{*c} N^{*g} \qquad (3.6)$$

Where : L_Y^*, K_Y^*, N^* are given by equations (3.1c, 3.2c and 3.4b), respectively.

Solving equation (2.43) provides the steady state optimal fertilizer use as follows

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

$$F^* = \left\{ \beta_2 Y^* - \beta_3 \left[Z - \tau e^{-\alpha L_S^*} + \phi(1 - e^{-vY}) \right] \right\} / \beta_1 \qquad (3.7)$$

Where : Y^* and L_S^* are given by equations (3.6 and 3.5), respectively.

Appendix IV. Current Value Hamiltonian Version and Derivation of Reduced form Solutions for the problem of physical soil degradation and nutrient mining (scenario II)

The current value Hamiltonian of this scenario is given by:

$$\Pi_C(F, L_Y, L_S, K_Y, SD, \mathrm{N}, \psi, \eta) = Pf(L_Y, K_Y, SD, N) - \left(W_F F + W_L L_Y + W_S L_S + W_K K_Y\right)$$
$$+\psi[H(Z, L_S, Y)] + \eta[G(F) - D(Y) + M(Z, L_S, Y)] \tag{4.1}$$

$$\text{Where}: \psi = e^{\delta t}\lambda \text{ and } \eta = e^{\delta t}\mu \tag{4.2}$$

The FOC for this system :

$$\frac{\partial \Pi_C}{\partial F} = -W_F + \eta \frac{\partial G}{\partial F} = 0 \tag{4.3}$$

$$\frac{\partial \Pi_C}{\partial L_Y} = P\frac{\partial f}{\partial L_Y} - W_L + \psi \frac{\partial H}{\partial L_Y} - \eta \frac{\partial D}{\partial L_Y} + \eta \frac{\partial M}{\partial L_Y} = 0 \tag{4.4}$$

$$\frac{\partial \Pi_C}{\partial K_Y} = P\frac{\partial f}{\partial K_Y} - W_K + \psi \frac{\partial H}{\partial K_Y} - \eta \frac{\partial D}{\partial K_Y} + \eta \frac{\partial M}{\partial K_Y} = 0 \tag{4.5}$$

$$\frac{\partial \Pi_C}{\partial L_S} = -W_L + \psi \frac{\partial H}{\partial L_S} + \eta \frac{\partial M}{\partial L_S} = 0 \tag{4.6}$$

$$\dot{\psi} = \delta\psi - \frac{\partial \Pi_C}{\partial SD} = \delta\psi - P\frac{\partial f}{\partial SD} - \psi\frac{\partial H}{\partial SD} + \eta\left(\frac{\partial D}{\partial SD} - \frac{\partial M}{\partial SD}\right) \tag{4.7}$$

$$\dot{\eta} = \delta\eta - \frac{\partial \Pi_C}{\partial N} = \delta\eta - P\frac{\partial f}{\partial N} - \psi\frac{\partial H}{\partial N} + \eta\left(\frac{\partial D}{\partial N} - \frac{\partial M}{\partial N}\right) \tag{4.8}$$

$$\frac{\partial \Pi_c}{\partial \psi} = \dot{SD} = Z - E + J \tag{4.9}$$

$$\frac{\partial \Pi_c}{\partial \eta} = \dot{N} = G(F) - D(Y) + M(Z, L_S, Y) \tag{4.10}$$

In a steady state the rate of change of the resource stock and hence the implicit prices are zero. That is $\dot{\psi} = \dot{\eta} = \dot{N} = \dot{SD} = 0$.

The first order conditions could, therefore, be restated as follows:

$$\eta = \frac{W_F}{G_F} \tag{4.3b}$$

$$\eta = \frac{(Pf_{L_Y} - W_L) + \psi H_{L_y}}{D_{L_Y} - M_{L_Y}} \tag{4.4b}$$

$$\eta = \frac{(Pf_{K_Y} - W_K) + \psi H_{K_Y}}{D_{K_Y} - M_{K_Y}} \tag{4.5b}$$

$$\eta = \frac{W_S - \psi H_{L_S}}{M_{L_S}} \tag{4.6b}$$

$$\eta = \frac{Pf_{SD} + \psi(H_{SD} - \delta)}{D_{SD} - M_{SD}} \tag{4.7b}$$

$$\eta = \frac{Pf_N + \psi H_N}{D_N - M_N + \delta} \tag{4.8b}$$

$$Z = E - J \tag{4.9b}$$

$$G(F) = D(Y) - M(Z, L_S, Y)] \tag{4.10b}$$

Equation (4.9b) above states that at the steady state the net rate of natural soil regeneration (Z) is exactly matched by the net soil loss due to erosion and cultivation (*E-J*). Analogously, equation (4.10b) describes that the sum of nutrients lost through crop harvest, damage function D(Y) and net nutrient gains/losses though M are matched by the nutrients added to the soil through the nutrient augmentation function G(F).

Combining equations 4.3b with each of 4.4b through 4.8b and eliminating η, the following equations are derived:

$$\psi = \frac{(W_F / G_F)(D_{L_Y} - M_{L_Y}) - (Pf_{L_y} - W_L)}{H_{L_Y}} \tag{4.11}$$

$$\psi = \frac{-[(W_F / G_F) M_{L_S} - W_S]}{H_{L_S}} \tag{4.12}$$

$$\psi = \frac{(W_F / G_F)(D_{K_Y} - M_{K_Y}) - (Pf_{K_Y} - W_K)}{H_{K_Y}} \tag{4.13}$$

$$\psi = \frac{(W_F / G_F)(D_{SD} - M_{SD}) - Pf_{SD}}{H_{SD} - \delta} \tag{4.14}$$

$$\psi = \frac{(W_F / G_F)(D_N - M_N + \delta) - Pf_N}{H_N} \tag{4.15}$$

Further combining equations (4.11 through 4.13) first with Equations (4.14) and then with equation (4.15), the following equations are derived.

$$Pf_N + \frac{H_N}{H_{L_Y}}\left[\left(\frac{W_F}{G_F}\right)(D_{L_Y} - M_{L_Y}) - (Pf_{L_y} - W_L)\right] = \frac{W_F}{G_F}(\delta + D_N - M_N) \tag{4.16}$$

$$Pf_N + \frac{H_N}{H_{K_Y}}\left[\left(\frac{W_F}{G_F}\right)(D_K - M_K) - (Pf_K - W_K)\right] = \frac{W_F}{G_F}(\delta + D_N - M_N) \tag{4.17}$$

$$Pf_N + \frac{H_N}{H_{L_S}}\left[(W_S - M_{L_S})\left(\frac{W_F}{G_F}\right)\right] = \frac{W_F}{G_F}(\delta + D_N - M_N) \tag{4.18}$$

$$Pf_{SD} + \left(\frac{H_{SD} - \delta}{H_{L_Y}}\right)\left[\left(\frac{W_F}{G_F}\right)(D_{L_y} - M_{L_Y}) - (Pf_{L_Y} - W_L)\right] = \frac{W_F}{G_F}(D_{SD} - M_{SD}) \quad (4.19)$$

$$Pf_{SD} + \left(\frac{H_{SD} - \delta}{H_{K_Y}}\right)\left[\left(\frac{W_F}{G_F}\right)(D_K - M_K) - (Pf_K - W_K)\right] = \frac{W_F}{G_F}(D_{SD} - M_{SD}) \quad (4.20)$$

$$Pf_{SD} + \left(\frac{H_{SD} - \delta}{H_{L_S}}\right)\left[(W_S - M_{L_S})\left(\frac{W_F}{G_F}\right)\right] = \frac{W_F}{G_F}(D_{SD} - M_{SD}) \quad (4.21)$$

The above equations along with equations (4.9b) and (4.10b) form a system of eight equations with eight unknowns and could be solved simultaneously for optimal steady state values of the four choice variables (F, L_Y, K_Y, L_S), the optimal resource stocks (SD and N) and the respective dynamic prices (Ψ and η).

Given the above formulations and the functional relationships given in Appendix II equations (4.16 – 4.21) and (4.9b and 4.10b) are specified as follows:

$$PgY + \frac{g}{b}[W_F bY\xi - PbY + W_L L_Y)] = W_F(\delta N + gY\xi) \quad (4.22)$$

$$PgY + \frac{g}{c}[W_F cY\xi - PcY + W_K K_Y)] = W_F(\delta N + gY\xi) \quad (4.23)$$

$$PgY + \frac{\varphi gY}{\tau\alpha e^{-\alpha L_S}}\left[W_S - \beta_3 \tau\alpha e^{-\alpha L_S}\right] = W_F(\delta N + gY\xi) \quad (4.24)$$

$$PdY + \left(\frac{\varphi dY - \delta SD}{\varphi bY}\right)\left[W_F bY\xi - PbY + W_L L_{L_Y}\right] = W_F dY\xi \quad (4.25)$$

$$PdY + \left(\frac{\varphi dY - \delta SD}{\varphi cY}\right)\left[W_F cY\xi - PcY + W_K K_{_Y}\right] = W_F dY\xi \quad (4.26)$$

$$PdY + \left(\frac{\varphi dY - \delta SD}{\tau\alpha e^{-\alpha L_S}}\right)\left[W_S - \beta_3 \tau\alpha e^{-\alpha L_S}\right] = W_F dY\xi \quad (4.27)$$

$$Z = \tau e^{-\alpha L_S} - \phi(1 - e^{-vY}) \tag{4.28}$$

$$\beta_1 F = \beta_2 Y - \beta_3 [Z - \tau e^{-\alpha L_S} + \phi(1 - e^{vY})] \tag{4.29}$$

Using the above formulations, the reduced form solutions for the choice variables (L_Y, L_S, K_Y and F) and the optimal nutrient stocks (N and SD) are solved as follows:

Using equation (4.22) to solve for L_Y:

$$PgY + \left(\frac{g}{b}\right)(W_F bY\xi - PbY + W_L L_Y) = W_F \delta N + W_F gY\varepsilon$$

$$PgY + gW_F Y\xi - gPY + \frac{g}{b} W_L L_Y = W_F \delta N + W_F gY\varepsilon$$

$$\frac{g}{b} W_L L_Y = W_F \delta N$$

$$L_Y = \frac{W_F \delta b}{gW_L} N = \left(\frac{W_F \delta}{g}\right)\left(\frac{b}{W_L}\right) N \tag{4.30a}$$

Using equation (4.23) to solve for K_Y:

$$PgY + \left(\frac{g}{c}\right)(W_F cY\xi - PcY + W_K K_Y) = W_F \delta N + W_F gY\varepsilon$$

$$PgY + gW_F Y\xi - gPY + \frac{g}{c} W_K K_Y = W_F \delta N + W_F gY\varepsilon$$

$$\frac{g}{c} W_K K_Y = W_F \delta N$$

$$K_Y = \frac{W_F \delta c}{gW_K} N = \left(\frac{W_F \delta}{g}\right)\left(\frac{c}{W_K}\right) N \tag{4.31a}$$

Using equation (4.25) to solve for SD:

$$PdY + \left(\frac{\varphi dY - \delta SD}{\varphi bY}\right)(W_F bY\xi - PbY + W_L L_Y) = W_F dY\varepsilon$$

$$\varphi bYPdY + \varphi dYW_F bY\xi - \varphi dYPbY + \varphi dYW_L L_Y - \delta SDW_F bY\xi + \delta SDPbY - \delta SDW_L L_Y = W_F dY\xi\varphi bY$$

$$\varphi dYW_L L_Y - \delta SDW_F bY\xi + \delta SDPbY - \delta SDW_L L_Y = 0$$

$$\varphi dYW_L L_Y - \delta SDW_F bY\xi + \delta SDPbY = \delta SDW_L L_Y$$

$$Y(\varphi dW_L L_Y - \delta SDW_F b\xi + \delta SDPb) = \delta SDW_L L_Y$$

$$Y = \frac{\delta SDW_L L_Y}{(\varphi dW_L L_Y - \delta SDW_F b\xi + \delta SDPb)}$$

$$\frac{Y}{L_Y} = \frac{\delta SDW_L}{b\delta SD(P - W_F\xi) + \varphi dW_L L_Y} \tag{4.32}$$

Equating equations (4.25 and 4.27) and solving

$$PdY + \left(\frac{\varphi dY - \delta SD}{\varphi bY}\right)(W_F bY\xi - PbY + W_L L_Y) = PdY + \left(\frac{\varphi dY - \delta SD}{\gamma\alpha e^{-\alpha L_S}}\right)(W_L - \beta_3\gamma\alpha e^{-\alpha L_S})$$

$$W_F bY\xi - PbY + W_L L_Y = \frac{\varphi bY}{\gamma\alpha e^{-\alpha L_S}}(W_L - \beta_3\gamma\alpha e^{-\alpha L_S})$$

$$W_F bY\xi - PbY + W_L L_Y = \frac{\varphi bYW_L e^{\alpha L_S}}{\gamma\alpha} - \beta_3\varphi bY$$

$$\frac{\varphi bYW_L e^{\alpha L_S}}{\gamma\alpha} - \beta_3\varphi bY - W_F bY\xi + PbY = W_L L_Y$$

$$bY\left(\frac{\varphi W_L e^{\alpha L_S}}{\gamma\alpha} - \beta_3\varphi - W_F\xi + P\right) = W_L L_Y$$

$$\frac{Y}{L_Y} = \frac{W_L}{b\left[\varphi\left(\frac{W_L e^{\alpha L_S}}{\gamma\alpha} - \beta_3\right) + (P - W_F\xi)\right]}$$

$$\text{Let}: \varphi\left(\frac{W_L e^{\alpha L_S}}{\gamma\alpha} - \beta_3\right) = \zeta, \text{ hence}$$

$$\frac{Y}{L_Y} = \frac{W_L}{b(\zeta + P - W_F\xi)} \qquad (4.33)$$

Further equating equation (4.32 and 4.33)

$$\frac{\delta SDW_L}{b\delta SD(P - W_F\xi) + \varphi dW_L L_Y} = \frac{W_L}{b(\zeta + P - W_F\xi)}$$

$$\delta SDb(\zeta + P - W_F\xi) = b\delta SD(P - W_F\xi) + \varphi dW_L L_Y$$

$$\delta SDb(\zeta + P - W_F\xi) - b\delta SD(P - W_F\xi) = \varphi dW_L L_Y$$

$$\delta SDb(\zeta + P - W_F\xi - P + W_F\xi) = \varphi dW_L L_Y$$

$$\delta SDb\zeta = \varphi dW_L L_Y$$

$$SD = \left(\frac{\varphi d}{\delta\zeta}\right)\left(\frac{W_L}{b}\right)L_Y \qquad (4.34a)$$

Substituting equations (4.30a) into the above equation (4.34a)

$$SD = \left(\frac{\varphi d}{\delta\zeta}\right)\left(\frac{W_L}{b}\right)\left(\frac{W_F\delta}{g}\right)\left(\frac{b}{W_L}\right)N$$

$$SD = \left(\frac{\varphi d}{\delta\zeta}\right)\left(\frac{W_F\delta}{g}\right)N \qquad (4.34b)$$

Solving for N using equations (4.30a, 4.31a, 4.33 and 4.34b)

From equation (4.33), we have

$$\frac{Y}{L_Y} = \frac{W_L}{b(\zeta + P - W_F\xi)}$$

Y has been specified as: $Y = AL_Y^b K_Y^c N^g SD^g$

Hence, $\frac{Y}{L_Y} = AL_Y^{b-1} K_Y^c N^g SD^g = \left(\frac{W_L}{b}\right)\left(\frac{1}{\zeta + P - W_F\xi}\right)$

Substituting equations (4.30a, 4.31a, and 4.34b) for L_Y, K_Y and SD, respectively, into the above equation and solving for N:

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

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

Let: $g + d + c + b - 1 = \theta$, Substituting and solving for N:

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

$$N^{*} = A^{\frac{-1}{\theta}}\left(\frac{W_F\delta}{g}\right)^{-\left(\frac{d+c+b-1}{\theta}\right)}\left(\frac{b}{W_L}\right)^{\frac{-b}{\theta}}\left(\frac{c}{W_K}\right)^{\frac{-c}{\theta}}\left(\frac{\varphi d}{\delta\zeta}\right)^{\frac{-d}{\theta}}\left(\frac{1}{\zeta+P-W_F\xi}\right)^{\frac{1}{\theta}} \quad (4.35)$$

Substituting the value of N from equation (4.35) into equation (4.30a) to solve for L_Y:

From equation (4.30a), we have,

$$L_Y = \left(\frac{W_F\delta}{g}\right)\left(\frac{b}{W_L}\right)N$$

Substituting equation (4.35) into the above equation and solving for L_Y:

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

$$L_Y^{*} = A^{\frac{-1}{\theta}}\left(\frac{W_F\delta}{g}\right)^{\frac{g}{\theta}}\left(\frac{b}{W_L}\right)^{\frac{g+d+c-1}{\theta}}\left(\frac{c}{W_K}\right)^{\frac{-c}{\theta}}\left(\frac{\varphi d}{\delta\zeta}\right)^{\frac{-d}{\theta}}\left(\frac{1}{\zeta+P-W_F\xi}\right)^{\frac{1}{\theta}} \quad (4.30b)$$

Likewise substituting the value of N from equation (4.35) into equation (4.31a) to solve for K_Y:

From equation (4.31a), we have,

$$K_Y = \left(\frac{W_F\delta}{g}\right)\left(\frac{c}{W_K}\right)N$$

Substituting equation (4.34) into the above equation

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

$$K_Y^* = A^{\frac{-1}{\theta}}\left(\frac{W_F\delta}{g}\right)^{\frac{g}{\theta}}\left(\frac{b}{W_L}\right)^{\frac{-b}{\theta}}\left(\frac{c}{W_K}\right)^{\frac{g+d+b-1}{\theta}}\left(\frac{\varphi d}{\delta\zeta}\right)^{\frac{-d}{\theta}}\left(\frac{1}{\zeta+P-W_F\xi}\right)^{\frac{1}{\theta}} \qquad (4.31b)$$

Substituting the value of N from equation (4.35) into equation (4.34b) to solve for the optimal value of SD:

From equation (4.34b), we have,

$$SD = \left(\frac{\varphi d}{\delta}\right)\left(\frac{1}{\zeta}\right)\left(\frac{W_F\delta}{g}\right)N$$

Substituting equation (4.34) into the above equation

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

$$SD^* = A^{\frac{-1}{\theta}}\left(\frac{W_F\delta}{g}\right)^{\frac{g}{\theta}}\left(\frac{b}{W_L}\right)^{\frac{-b}{\theta}}\left(\frac{c}{W_K}\right)^{\frac{-c}{\theta}}\left(\frac{\varphi d}{\delta\zeta}\right)^{\frac{g+c+b-1}{\theta}}\left(\frac{1}{\zeta+P-W_F\xi}\right)^{\frac{1}{\theta}} \qquad (4.34c)$$

Solving for the optimal value of L_S using equations (4.24 and 4.27)

From equation (4.27)

$$PdY + \left(\frac{\varphi dY - \delta SD}{\gamma\alpha e^{-\alpha L_S}}\right)\left(W_S - \beta_3\gamma\alpha e^{-\alpha L_S}\right) = W_F dY\varepsilon$$

$$PdY + (\varphi dY - \delta SD)\left(\frac{W_S e^{\alpha L_S}}{\gamma\alpha} - \beta_3\right) = W_F dY\varepsilon$$

$$PdY + \frac{\varphi dY W_S e^{\alpha L_S}}{\gamma\alpha} - \varphi dY\beta_3 - \frac{\delta SDW_S e^{\alpha L_S}}{\gamma\alpha} + \delta SD\beta_3 = W_F dY\varepsilon$$

$$PdY + \frac{\varphi dY W_S e^{\alpha L_S}}{\gamma\alpha} - \varphi dY\beta_3 - W_F dY\varepsilon = \frac{\delta SDW_S e^{\alpha L_S}}{\gamma\alpha} - \delta SD\beta_3$$

$$dY\left(P + \frac{\varphi W_S e^{\alpha L_S}}{\gamma\alpha} - \varphi\beta_3 - W_F\varepsilon\right) = \delta SD\left(\frac{W_S e^{\alpha L_S}}{\gamma\alpha} - \beta_3\right)$$

$$Y = \frac{\delta SD\left(\frac{W_S e^{\alpha L_S}}{\gamma\alpha} - \beta_3\right)}{d\left(P + \frac{\varphi W_S e^{\alpha L_S}}{\gamma\alpha} - \varphi\beta_3 - W_F\varepsilon\right)} = \left(\frac{\delta SD}{d}\right)\left[\frac{\left(\frac{W_S e^{\alpha L_S}}{\gamma\alpha} - \beta_3\right)}{\varphi\left(\frac{W_S e^{\alpha L_S}}{\gamma\alpha} - \beta_3\right) + (P - W_F\varepsilon)}\right]$$

Since : $\varphi\left(\frac{W_S e^{\alpha L_S}}{\gamma\alpha} - \beta_3\right) = \zeta$, the above equation could be rewritten as

$$Y = \left(\frac{\delta}{d}\right)\frac{\left(\frac{W_S e^{\alpha L_S}}{\gamma\alpha} - \beta_3\right)}{(\zeta + P - W_F\varepsilon)}SD \qquad (4.36)$$

Similarly using equation (4.24)

$$PgY + \left(\frac{\varphi gY}{\gamma\alpha e^{-\alpha L_S}}\right)\left(W_S - \beta_3\gamma\alpha e^{-\alpha L_S}\right) = W_F(\delta N + gY\varepsilon)$$

$$PgY + \frac{\varphi g Y W_S}{\gamma \alpha e^{-\alpha L_S}} - \beta_3 \varphi g Y = W_F \delta N + W_F g Y \varepsilon$$

$$PgY + \frac{\varphi g Y W_S}{\gamma \alpha e^{-\alpha L_S}} - \beta_3 \varphi g Y - W_F g Y \varepsilon = W_F \delta N$$

$$gY\left(P + \frac{\varphi W_S}{\gamma \alpha e^{-\alpha L_S}} - \beta_3 \varphi - W_F \varepsilon \right) = W_F \delta N$$

$$Y = \frac{W_F \delta N}{g\left(P + \frac{\varphi W_S}{\gamma \alpha e^{-\alpha L_S}} - \beta_3 \varphi - W_F \varepsilon \right)} = \left(\frac{W_F \delta}{g} \right) \left[\frac{1}{\varphi\left(\frac{\varphi W_S}{\gamma \alpha e^{-\alpha L_S}} - \beta_3 \right) + (P - W_F \varepsilon)} \right] N$$

$$Y = \left(\frac{W_F \delta}{g} \right) \left(\frac{1}{\zeta + P - W_F \varepsilon} \right) N \qquad (4.37)$$

Equating equations (4.36 and 4.37) to solve for L_S:

$$\left(\frac{\delta}{d} \right) \frac{\left(\frac{W_S e^{\alpha L_S}}{\gamma \alpha} - \beta_3 \right)}{(\zeta + P - W_F \varepsilon)} SD = \left(\frac{W_F \delta}{g} \right) \left(\frac{1}{\zeta + P - W_F \varepsilon} \right) N$$

$$\frac{W_S e^{\alpha L_S}}{\gamma \alpha} - \beta_3 = \left(\frac{W_F \delta}{g} \right) \left(\frac{d}{\delta} \right) \frac{N^*}{SD^*}$$

Substituting equations (4.35 and 4.34c) for N^* and SD^* and solving

$$\frac{W_S e^{\alpha L_S}}{\gamma \alpha} - \beta_3 = \frac{\zeta}{\varphi}$$

$$e^{\alpha L_S} = \frac{\gamma \alpha}{W_S} \left(\frac{\zeta}{\varphi} + \beta_3 \right)$$

$$\alpha L_S = \ln\left[\frac{\gamma\alpha}{W_S}\left(\frac{\zeta}{\varphi} + \beta_3\right)\right]$$

$$L_S^* = \left(\frac{1}{\alpha}\right)\ln\left[\frac{\gamma\alpha}{W_S}\left(\frac{\zeta}{\varphi} + \beta_3\right)\right] \quad (4.38)$$

Given the optimal values for L_Y, K_Y, N and SD above, the optimal output at a desirable steady state is given by:

$$Y^* = AL_Y^{*b} K_Y^{*c} N^{*g} SD^{*d} \quad (4.39)$$

Where : L_Y^*, K_Y^*, N^* and SD^* are given by equations (4.30b, 4.31b, 4.35 and 4.34c), respectively

Solving equation (4.29) provides the steady state optimal fertilizer use:

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

$$F^* = \left\{\beta_2 Y^* - \beta_3\left[Z - \tau e^{-\alpha L_S^*} + \phi(1 - e^{-\nu Y})\right]\right\} / \beta_1 \quad (4.40)$$

Where : Y^* and L_S^* are given by equations (4.39 and 4.38), respectively.

Appendix V. Derivation of static optimal solutions

$$Max\Pi(F, L_Y, L_S, K_Y) = Pf(L_Y, K_Y, F) - W_F F - W_L L_Y - W_K K_Y \quad (5.1)$$

The FOC for this system :

$$\frac{\partial \Pi}{\partial F} = P\frac{\partial f}{\partial F} - W_F = 0 \Rightarrow \frac{PgY}{F} = W_F \quad (5.2)$$

$$\frac{\partial \Pi}{\partial L_Y} = P\frac{\partial f}{\partial L_Y} - W_L = 0 \Rightarrow \frac{PbY}{L_Y} = W_L \quad (5.3)$$

$$\frac{\partial \Pi}{\partial K_Y} = P\frac{\partial f}{\partial K_Y} - W_K = 0 \Rightarrow \frac{PcY}{K_Y} = W_K \quad (5.4)$$

Equations (5.2 to 5.4) could be solved simultaneously for the optimal values of L_Y, K_Y and F as follows.

Combining equations (5.2 and 5.3),

$$\frac{PgY}{F} * \frac{L_Y}{PbY} = \frac{W_F}{W_L}$$

$$L_Y = \frac{W_F}{g}\frac{b}{W_L}F \quad (5.5)$$

Combining equations 5.2 and 5.4

$$\frac{PgY}{F} * \frac{K_Y}{PcY} = \frac{W_F}{W_K}$$

$$K_Y = \frac{W_F}{g}\frac{c}{W_K}F \quad (5.6)$$

Combining equations 5.3 and 5.4

$$\frac{PbY}{L_Y} * \frac{K_Y}{PcY} = \frac{W_L}{W_K}$$

$$K_Y = \frac{W_L}{b}\frac{c}{W_K}L_Y \qquad (5.7)$$

Solving for L_Y using equation 5.2:

$$\frac{PgY}{F_Y} = W_F$$

Since, $Y = AL_Y^b K_Y^c F^g$, the above can be written as :

$$AL_Y^b K_Y^c F^{g-1} = \frac{W_F}{gP}$$

Substituting equations (5.5 and 5.6) into the above expression

$$A\left(\frac{W_F}{g}\frac{b}{W_L}F\right)^b\left(\frac{W_F}{g}\frac{c}{W_K}F\right)^c F^{g-1} = \frac{W_F}{gP}$$

$$F^{g+c+b-1}\left(\frac{W_F}{g}\right)^{c+b}\left(\frac{b}{W_L}\right)^b\left(\frac{c}{W_K}\right)^c = \frac{W_F}{PAg}$$

Let $1 - g - c - b = \varpi$, then $g + c + b - 1 = -\varpi$

Substituting and solving for F:

$$F^{-\varpi} = \left(\frac{W_F}{g}\right)^{1-c-b}\left(\frac{b}{W_L}\right)^{-b}\left(\frac{c}{W_K}\right)^{-c}\left(\frac{1}{PA}\right)$$

$$F^* = \left(\frac{1}{PA}\right)^{-\frac{1}{\varpi}}\left(\frac{b}{W_L}\right)^{\frac{b}{\varpi}}\left(\frac{c}{W_K}\right)^{\frac{c}{\varpi}}\left(\frac{W_F}{g}\right)^{\frac{c+b-1}{\varpi}} \qquad (5.8)$$

Solving for L_Y using equation (5.5):

$$L_Y = \frac{W_F}{g}\frac{b}{W_L}F$$

Substituting equation (5.8) into the above expression and solving for L_Y:

$$L_Y = \frac{W_F}{g}\frac{b}{W_L}\left(\frac{W_F}{g}\right)^{\frac{c+b-1}{\varpi}}\left(\frac{b}{W_L}\right)^{\frac{b}{\varpi}}\left(\frac{c}{W_K}\right)^{\frac{c}{\varpi}}\left(\frac{1}{PA}\right)^{-\frac{1}{\varpi}}$$

$$L_Y^* = \left(\frac{1}{PA}\right)^{-\frac{1}{\varpi}}\left(\frac{b}{W_L}\right)^{\frac{1-g-c}{\varpi}}\left(\frac{c}{W_K}\right)^{\frac{c}{\varpi}}\left(\frac{W_F}{g}\right)^{-\frac{g}{\varpi}} \qquad (5.9)$$

Solving for L_K using equation (5.7),

$$K_Y = \frac{W_L}{b}\frac{c}{W_K}L_Y$$

Substituting equation (5.9) into the above expression

$$K_Y = \frac{W_L}{b}\frac{c}{W_K}\left(\frac{1}{PA}\right)^{-\frac{1}{\varpi}}\left(\frac{W_F}{g}\right)^{-\frac{g}{\varpi}}\left(\frac{b}{W_L}\right)^{\frac{1-g-c}{\varpi}}\left(\frac{c}{W_K}\right)^{\frac{c}{\varpi}}$$

$$K_Y^* = \left(\frac{1}{PA}\right)^{-\frac{1}{\varpi}}\left(\frac{b}{W_L}\right)^{\frac{b}{\varpi}}\left(\frac{c}{W_K}\right)^{\frac{1-g-b}{\varpi}}\left(\frac{W_F}{g}\right)^{-\frac{g}{\varpi}} \qquad (5.10)$$

Appendix VI. Soil loss for two plot categories estimated using the USLE modified for Ethiopia

Conservation structure	Crop type	Plot category	Rainfall erosivity R	Soil erodibility K	Slop length L	Slop gradient S	Land cover C	Management factor P	Soil loss (Ton/ha)
No	Tef	Uplands	430.2	0.25	2.1	1.78	0.25	0.75	75.38
No	Tef	Bottomlands	430.2	0.15	3.5	0.4	0.25	0.75	16.94
Yes	Tef	Uplands	430.2	0.25	0.6	1.78	0.25	0.9	25.84
Yes	Tef	Bottomlands	430.2	0.15	1.2	0.4	0.25	0.9	6.97
No	Other cereals	Uplands	430.2	0.25	2.1	1.78	0.18	0.75	54.27
No	Other cereals	Bottomlands	430.2	0.15	3.5	0.4	0.18	0.75	12.20
Yes	Other cereals	Uplands	430.2	0.25	0.6	1.78	0.18	0.9	18.61
Yes	Other cereals	Bottomlands	430.2	0.15	1.2	0.4	0.18	0.9	5.02
No	Pulses	Uplands	430.2	0.25	2.1	1.78	0.15	0.75	45.23
No	Pulses	Bottomlands	430.2	0.15	3.5	0.4	0.15	0.75	10.16
Yes	Pulses	Uplands	430.2	0.25	0.6	1.78	0.15	0.9	15.51
Yes	Pulses	Bottomlands	430.2	0.15	1.2	0.4	0.15	0.9	4.18

Source: Shiferaw and Holden (1999)

Appendix VII. Parameter estimates of the multinomial logit soil fertility adoption model, Central highlands of Ethiopia, 2003

Explanatory Variables	Seasonal fallowing (SF) or Crop rotations (LG)		Animal manure (AM) alone		Animal manure associated with wither SF or LR		Inorganic fertilizers (IF) alone		Inorganic fertilizer associated with either SF, LR or MR	
	Coefficient	Prob.	Coefficient	Prob.	Coefficient	Prob.	Coefficient	Prob.	Coefficient	Prob.
Constant	-3.6566***	0.000	-1.4414***	0.003	-3.3788***	0.000	-2.8492***	0.000	-3.9765***	0.000
Education	0.0327	0.378	0.1124***	0.042	0.0897	0.130	0.0324	0.634	0.1371***	0.007
Off-farm income	0.1462	0.476	-0.1372	0.609	-0.1457	0.698	0.5326	0.216	0.4205	0.167
Livestock	-0.0137	0.582	0.0295	0.305	0.0136	0.747	0.0741*	0.099	0.0944***	0.004
Plot size	2.3760***	0.000	0.1526	0.797	1.5744*	0.066	3.0165***	0.000	2.8956***	0.000
No. of plots	0.0365	0.349	-0.1194***	0.002	-0.0951*	0.085	-0.0070	0.935	-0.1786***	0.001
Plot distant	-0.0016	0.724	-0.1075***	0.000	-0.1086***	0.002	-0.0036	0.633	0.0040	0.432
Light	-0.1013	0.596	0.6588***	0.007	1.4831***	0.000	0.8180**	0.019	0.3381	0.261
Medium	-0.1109	0.627	0.1745	0.517	0.9849**	0.038	0.7563*	0.060	0.5645*	0.055
Sever	0.3095	0.262	-0.0326	0.932	0.8488	0.113	1.0768**	0.026	0.7690**	0.015
Tenure	0.0666	0.705	1.2011***	0.001	0.7503*	0.087	-0.4493	0.214	0.6156**	0.030
Credit	0.5557**	0.029	0.4815*	0.075	-0.1725	0.686	1.4017***	0.000	2.0172***	0.000
Extension	0.0094	0.981	0.2558	0.624	0.9767	0.145	1.1393*	0.063	0.9797*	0.052
Agro-ecology	3.1615***	0.000	0.9560***	0.001	1.6719***	0.001	-1.3625***	0.000	1.0375***	0.001
Kossi	-1.2191**	0.049	1.3675***	0.001	-0.0151	0.984	-0.8746	0.183	-0.6484	0.198
Diagnostics										
No. Observations	1411									
Wald Chi-Square	771.08***									
Log pseeudo likelihood	-1810.0929									
Pseudo R-Square	0.2314									

***, **, *= Significant at 1%, 5% and 10% probability level, respectively

Appendix VIII. Coefficient estimates of the multinomial logit soil conservation adoption model, Central highlands of Ethiopia, 2003

Variable	Cut-off drainage (golenta)		Stone and soil bunds	
	Coefficient	P-level	Coefficient	P-level
Constant	-3.3845***	0.000	-7.5696***	0.000
Education	0.0552	0.358	0.1192**	0.019
Plot area	-0.2998	0.302	0.5288	0.226
No. of plots	-0.0196	0.816	-0.0721	0.206
Plot distance	0.0079	0.263	-0.0027	0.640
Tenure	0.4967	0.163	0.3503	0.242
Livestock	0.0671	0.193	-0.0109	0.725
Off-farm income	-0.0814	0.854	-0.6829***	0.009
Extension	-0.2043	0.826	0.3214	0.577
Credit	-0.6764	0.169	-0.4494	0.224
Plot slope	0.2570	0.300	1.6694***	0.000
Soil degradation				
Sever	1.4714***	0.002	2.7903***	0.000
Medium	1.9818***	0.000	2.9154***	0.000
Light	1.9555***	0.000	2.9223***	0.000
Assistance	1.9876*	0.056	2.7938***	0.000
District	-1.2241**	0.043	4.2534***	0.000
Diagnostics				
No. Observations	97		309	
Wall Chi-Square	270.03***			
Pseudo Chi-Square	0.4017			

***, **, *= Significant at 1%, 5% and 10% probability levels, respectively

Appendix IX. Parameter estimates of the Tobit adoption model for the intensity of inorganic fertilizer use (kg/ha), Central highlands of Ethiopia, 2003

Variable			Marginal effects			
	Coefficient	P-level	Adoption (index)	P-level	Expected use (kg/ha)	P-level
Constant	-116.3897***	0.000	N.A.	N.A.	N.A.	N.A.
Education[1]	9.2427***	0.000	0.0210***	0.000	2.0126***	0.000
Off-farm income[2]	29.0357**	0.025	0.0689**	0.030	6.5489**	0.029
Livestock[3]	6.8069***	0.000	0.0154***	0.000	1.4822***	0.000
Plot size[4]	49.9898***	0.002	0.1133***	0.002	10.8850***	0.002
No. of plots	-10.4497***	0.000	-0.0237***	0.000	-2.2754***	0.000
Plot distant[5]	0.4583*	0.094	0.0010**	0.093	0.0998*	0.093
Severity of soil degradation[6]						
Light	21.8407*	0.097	0.0509	0.106	4.8545	0.104
Medium	38.0750***	0.004	0.0927***	0.007	8.7697***	0.007
Sever	39.4582**	0.013	0.0983**	0.022	9.2578**	0.021
Tenure[7]	17.9643	0.165	0.0391	0.146	3.8033	0.153
Credit[8]	99.6655***	0.000	0.2419***	0.000	23.2970***	0.000
Extension[9]	74.3334***	0.000	0.2017***	0.000	19.0840***	0.000
Agro-ecology[10]	-51.9767***	0.000	-0.1281***	0.000	-12.1180***	0.000
SFM used previous year[11]						
Legume rotations	-26.8184**	0.025	-0.0610	0.024	-5.8586**	0.025
Manure	-119.2528***	0.000	-0.2190	0.000	-23.1081***	0.000
Fallow	33.1012**	0.034	0.0806	0.046	7.6161**	0.044
District*Bund[12]	-20.5157	0.196	-0.0448	0.177	-4.3600	0.184
Diagnostics						
No. Observations	1293					
LR Chi-Square	492.44***	0.000				

***, **, *= Significant at 1%, 5% and 10% probability levels, respectively; N.A.=Not applicable; [1]Number of years; [2]Dummy variable, 1 denoting participation in off- farm activities; [3]Tropical Livestock Unit (TLU); [4]hectares; [5]Minutes walked from residence; [6]comparison category is plots perceived not having shown any form of soil degradation; [7]dummy variable, 1 denoting PA allotted plots, 0 otherwise; [8]dummy variable, 1 denoting access to institutional credit; [9]dummy variable, 1 representing access to government extension; [10]dummy variable, 1 referring to upper highlands; [11]dummy variables with 1 indicating use of the respective practices. [12]dummy variable with 1 indicating plots with stone/soil bunds in Debre Berihan district.