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Dynamic costs of soil degradation and determinants of adoption of soil conservation technologies by smallholder farmers in Malawi.

by

Teddie Oliver Nakhumwa

Submitted in partial fulfillment of the requirements for the degree of

Ph.D.

in the

Department of Agricultural Economics, Extension and Rural Development
Faculty of Natural and Agricultural Sciences
University of Pretoria
South Africa
July 2004

Dedication

To my dear wife Candida and son Joshua-Thanthwe.

ACKNOWLEDGEMENTS

I am grateful to many people and institutions for making this thesis possible. Profound thanks and appreciation go to my supervisor, Professor Rashid Mekki Hassan, for his untiring support throughout my PhD program. I would also like to acknowledge with thanks his high intellectual guidance and importantly, patience, throughout the course of my work. His enormous contribution has really shaped this work to what it is.

This study has benefited from the financial support of the Centre for Environmental Economics and Policy in Africa (CEEPA) and the Rockefeller Foundation for which I am very grateful. Particularly, I would like to extend my heartfelt thanks to Dr Akin Adesina, Regional Representative of the Rockefeller Foundations for Southern Africa, Drs Mullugeta Mekuria and Stephen Waddington of CIMMYT (Harare, Zimbabwe) for their significant role in securing the financial support for my research work. I sincerely acknowledge my employers, the University of Malawi (Bunda College-Agricultural Policy Research Unit) for granting me study leave to pursue my post-graduate studies at the University of Pretoria.

I am deeply indebted also to Dr James Appiah Benhin for his invaluable comments and guidance at various stages of this work. My profound appreciation is also due to Dr Ramos Mabugu, Deputy Director of CEEPA, for his useful advice and encouragement. Sincere thanks are due to Dr George Kanyama-Phiri, Principal of Bunda College of Agriculture and Dr MAR Phiri, for their support in securing research funds for this work. Special thanks should also go to Dr A. R. Saka of the Ministry of Agriculture and Irrigation in Malawi and Mr. Vincent Mkandawire of JICA-Malawi for their invaluable contributions to this work. The following people were quite instrumental and provided me with invaluable advice at the planning stage of my research work in Malawi: Dr Todd Benson of IFPRI, Washington, D.C., Drs Julius Mangisoni and Kenneth Wiyo of Bunda College of Agriculture and Mr Mlava (Bunda College). I really appreciate their contributions. I am also thankful to Mr Chirwa (Bunda College, Soil Science Dept), who assisted me with soil analysis.

I have treasured the comfort and encouragement received from fellow PhD students in particular the following: Mampiti Matete, Patrick Birungi, Moses Sichei, James Juana, Rose Emongor, Adelaide Matlanyane, Jethro Zuwarimwe, Oyenuga Oyenike, Glwadyes Gbetibouo, Charles Abukar, Chilot Y. Tizale, and Benjamin Banda.

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Many thanks also go to these dear friends for their support and encouragement: Eric and Alice Mkanda, Denis and Agnes Mwangwela, Timothy and Rose Tieku, John and Grace Muringe, and Prince Kapondamgaga. My two big families in Malawi, the waiting has been too long but you patiently endured. My sister Caroline-Rose has been a reliable source of encouragement for me. The profound love and vision of Abigail has brought me this far. You decorated my life!

Finally, the love and great strength of my "dear wife and best friend" Candida and son Joshua-Thanthwe, really inspired me throughout the period. I really thank you guys for your untiring patience and understanding, but most of all, enduring love.

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by

Teddie Oliver Nakhumwa

Degree:	PhD
Department:	Agricultural Economics, Extension and Rural Development
Promoter:	Professor Rashid Mekki Hassan

Abstract

This thesis aimed at measuring the economic costs of soil degradation and to determine factors that influence the incidence and extent of adoption of soil conservation technologies by smallholder farmers in Malawi. A dynamic optimisation model was used to derive and analyse the optimal conditions for soil resource extraction and use in Malawi, while a selective tobit model was used to simulate the two-step decision-making process of farmers with respect to adoption of soil conservation technologies.

Soil degradation has long-term consequences and static models, which form the bulk of studies that have so far been carried out in Africa on this topic, do not account for the inter-temporal dimension of optimal resource management. To deal with this shortcoming, this thesis used an inter-temporal optimisation framework, which considers soil in a time-dependent resource extraction perspective. This thesis has demonstrated that soil degradation is causing an enormous reduction in the productive value of smallholder land in Malawi. Current user cost of soil quality based on current practices of

smallholder farmers, which estimated to be US$21 per hectare. Based on this value and land area under smallholder agriculture in Malawi, economic costs of soil degradation among smallholder farmers were estimated to amount to 14 per cent of the agricultural GDP. If left unabated, soil degradation threatens not only the future of smallholder agriculture but also, economic growth prospects of the nation.

Although not operating on the SS optimal path in terms of soil resource management, current practices show that smallholder farmers in Malawi still consider, to certain degree, the dynamic costs in soil resource use. Hence, there is no strong evidence to suggest that current trends in land degradation are due to an institution failure (i.e., smallholder farmers have private incentives to conserve their soil resource). A result that suggests presence of other factors, most likely market distortions, behind existing deviations of farmers' practices from dynamic optimum. Government's serious support of the input and output market reforms is important not only to make the markets work but also, to make smallholder agriculture a profitable enterprise. It is only when smallholder agriculture becomes profitable that farmers can seriously invest in the soil resource. Agricultural support programs such as "food for work" if extended to include soil conservation, could lead to substantial curtailment of soil erosion since farmers can invest their labour in their own gardens during the critical times of land preparation.

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

The study estimated an optimal output of 1.5ton/ha and nitrogen fertiliser rate of 49 kg/ha at SS. The fertiliser estimates are based on smallholder farming system that incorporates soil conservation. In one of the most detailed studies on nitrogen use efficiency in

Malawi, Itimu (1997) indicated that with the incorporation of manure, nitrogen fertiliser use dropped from 60 to 30 kg/ha to produce about 2.5 tons of maize. Malawi uses area specific recommendations for fertiliser application. However, using "best bet" technologies, at least 35kgN/ha is recommended for smallholder farmers on average. The SS optimum fertiliser estimated in the current study was somehow higher due to the fact that an inter-temporal framework, which considered the dynamic costs of soil nutrient extraction, was used. Results from fertiliser recommendation trials may be reinforced if researchers consider the inter-temporal nature and dynamic costs associated with the use of soil.

The selective tobit model results indicate that factors that influence smallholder farmers' decisions to adopt soil conservation technologies may not necessarily be the same factors that influence subsequent decision on levels of adoption. The implication of this finding is that different policy prescriptions on soil conservation should strictly be guided by the goals the government wants to achieve. With fertiliser prices being out of the reach of most smallholder farmers in Malawi, soil conservation is one of the reliable options available to reduce soil degradation. However, any policy aimed at improving adoption of soil conservation technologies among smallholder farmers would succeed only if the various needs of smallholder farmers at the two decision stages are properly identified and addressed.

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ACRONYMS AND ABBREVIATIONS

ADD	Agricultural Development Division
ADMARC	Agricultural Development and Marketing Corporation
ALDSAP	Agriculture and Livestock Development Strategy &Action Plan
CD	Cobb Douglas
CEC	Cation Exchange Capacity
DFID	Department for International Development (Previously ODA)
EPA	Extension Planning Area
EPIC	Erosion Productivity Impact Calculator
FAO	Food and Agriculture Organisation
FEWS	Farming Early Warning System
GDP	Gross Domestic Product
GIS	Geographical Information System
GoM	Government of Malawi
IFDC	International Fertiliser Development Centre
IITA	International Institute for Tropical Agriculture
LUPMAP	Land Use Policy &Management Action Plan
MoAI	Ministry of Agriculture and Irrigation
MK	Malawian Kwacha
MLE	Maximum Likelihood Estimation
MPTF	Maize Productivity Task Force
NEAP	National Environmental Action Plan
NEC	National Economic Council
NGO	Non Governmental Organisation
NRI	Natural Resources Institute
NTRM	Nitrogen Tillage Residue Management
OLS	Ordinary Least Squares
PI	Productivity Index
PLCE	Presidential Land Commission of Enquiry
RDP	Rural Development Project

RUSLE	Revised Universal Soil Loss Equation
SLEMSA	Soil Loss Estimation Model for Southern Africa
SNA	System of National Accounts
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SSA	Sub-Saharan Africa
TIP	Targeted Input Program
UNDP	United Nations Development Programme
UNEP	United Nations Environmental Programme
UNO	United Nations Organisation
USAID	United States Agency for International Development
US$	United States Dollar
USLE	Universal Soil Loss Equation

CHAPTER I

INTRODUCTION

1.1 Background and Statement of the Problem

Malawi, like most sub-Saharan African (SSA) countries, is faced with declining per capita food production since the 1980s (FAO, 1991). Declining soil fertility is the identified major cause of the declining per capita food production in Africa (El-Swaify et al., 1985). The nutrient resource base for SSA has been shrinking (Stoorvogel and Smaling, 1990). Soil erosion and soil nutrient mining through continuous cultivation of crops coupled with low application of external sources of nutrients is singled out as the major cause of nutrient depletion (declining soil fertility) in the region. The annual net nutrient depletion (due to soil erosion and soil mining) in Malawi and some other countries in the region exceeds 30kg N and 20kg K per ha of arable land [IFDC, 1999; Stoorvogel and Smaling, 1990]. The current average use of nutrients for Africa is about 10 kg NPK/ha/year while the estimated average use required to meet nutrient needs at current levels of production is about 40 kg NPK/ha/year. Therefore, increased agricultural productivity and food production in this region can only be attained through the enhancement of the agricultural resource base.

In Malawi, soil mining due to continuous cultivation of mostly maize (mono-cropping) by smallholder farmers is eroding the fertility and productivity of soils even in the absence of soil erosion. Estimates indicate that smallholder farmers, who occupy almost two thirds of the total harvested agricultural area in Malawi (1.98 million hectares), apply on average 26 kg of fertilizer per hectare of maize, which is far below crop and soil maintenance requirements (Heisey and Mwangi, 1995; FAO, 1994; UN, 1996). Actually, nutrient balances calculated for Malawi indicate a negative balance (IFDC, 1999;1985). Admittedly, continuous cultivation of maize, without adequate application of commercial or organic fertilizers to replenish the soils, as is the case of smallholders in Malawi, has elsewhere been linked to reduction in the organic matter content of soils, and consequently yield decline [Singh and Goma, 1995; Jones, 1972; Andersen, 1970, Grant; 1967]. Unless urgent attention is given to reverse the existing imbalance between the nutrient extraction by cultivated crops and nutrient additions from external sources, productivity of Malawian soils will continue to decline worsening further the food insecurity problem.

Also, urgent attention is required to curtail soil erosion and its degrading impact on soil productivity. Malawi is categorized as one of those countries with the highest level of soil erosion in sub-Saharan Africa (Bojo, 1996). Annual soil loss due to water-induced erosion in Malawi is about 20 ton/ha (Bishop, 1992). It is not surprising therefore, that soil erosion has been singled out as number one threat to sustainable agricultural development in the country (NEAP Secretariat, 1994). Noteworthy, there is low adoption levels of soil conservation technologies among smallholder farmers in Malawi [Mangisoni, 1999; Kumwenda, 1995]. However, small-scale soil conservation techniques are not only affordable to smallholder farmers, but also, quite effective in reducing soil erosion. As such, increased adoption of soil conservation techniques is, obviously, of strategic importance in reducing levels of soil erosion and, subsequently, improving productivity of smallholder farms.

In Malawi, rapid population growth is one of the factors blamed for land degradation as it has exerted much pressure on the agricultural land. However, the view that population pressure usually cause land degradation is sometimes disputed. Recent evidence shows that population and market pressure can be associated with adoption of land conservation techniques and even with reforestation [Templeton and Scherr, 1997; Tiffen et al., 1994]. Nevertheless, the impact of rapid population growth in Malawi is crucial when discussing the problem of land fragmentation and land use (cultivation of marginal lands). Land fragmentation and cultivation of marginal areas in Malawi is connected to the problem of land degradation. To begin with, about 85 per cent of the Malawian population earns their livelihood from agriculture. As such, the rapid population growth has exerted enormous pressure on the agricultural land. In Malawi, population pressure has been absorbed either by splitting further the already small pieces of land (land fragmentation) or by extending cultivation to marginal areas. For example, in 1977 only 37 per cent of the land was classified as suitable for crop production and 86.7 per cent of this land was already under cultivation (Phiri, 1984). Farming families with land size of less than one hectare were estimated to be 55 per cent for the same period (World Bank, 1987). However, this figure had risen to 76 per cent by 1997, with about 41 per cent cultivating less than half a hectare (FAO, 1998). It is inevitable that such rapid decrease in land size per farming family has seriously reduced smallholder farmers' ability to engage in fallow system as a way to recuperate its soil fertility.

Another issue linked to the rapid population growth in Malawi is the alarming increase in levels of poverty. Poverty situation has continued to worsen with now more than 70 per cent of farm families in Malawi classified as poor (FAO, 1998). The growing number of poor households means that fewer and fewer farm families can now afford commercial fertilizers. Chemical fertilizers have been successfully used in other parts of the world to replenish soil fertility. Although maintenance and enhancement of soil productivity hinges upon intensified use of external inputs such as commercial and organic fertilizers, and increased adoption of soil conservation technologies, there are key problems associated with either option for Malawi. Majority of smallholder farmers cannot afford commercial fertilisers due to high prices. Use of fertiliser among smallholder farmers is also hampered by poor delivery and distribution system mainly as a result of poor road and market infrastructure (Nakhumwa et al, 1999; Ng'ongola et al, 1997). Nevertheless, small-scale soil conservation technologies (physical and biological) and use of other cheaper external sources of soil nutrients such as organic manures remain the most affordable options for the majority of smallholder farmers in Malawi. Importantly, reasons for poor adoption of soil conservations technologies by smallholder farmers need to be clearly understood if policy makers are to indeed design proper and strategic interventions aimed at improving adoption among this category of farmers.

Noteworthy, short-term consequences of the declining soil fertility on agriculture and food security are well known at both farm and policy levels. Various studies linked to soil fertility issues have been carried out in Malawi over the years [Mangisoni 1999; Benson 1998; Bishop, 1992]. Some of the analyses carried out in Malawi and linked to soil fertility have included the following:1) crop (maize) response to major soil nutrients such as nitrogen and phosphorous; 2) fertilizer recommendations and levels of fertilizer use in the country; 3) quantifying amount of soil erosion taking place in the country and; 4) adoption levels of soil conservation technologies. However, Malawi's heavy dependence on agriculture entails that the country cannot relax its efforts to preserve land quality bearing in mind it must provide adequately for the well being of both the current and future generations. In order to properly consider the importance of land quality for agricultural productivity in Malawi, it is crucial for policy makers and farmers alike to understand the long-term and dynamic nature of soil erosion and soil-mining problems and their consequent implications. For example, policy makers and farmers need to have knowledge of what is happening to the soil as a productive asset i.e., declining quality due to agricultural production, and its devastating impact on productivity over time. Ignoring the long-term costs of land degradation leads to formulation of unsustainable policy prescriptions based on limited assessment of short-term costs and benefits. Assessment of dynamic costs of soil degradation on agricultural productivity and inevitably, social well being of the people of Malawi, generates some quite useful information that can be used by policy makers in formulating more proactive soil fertility enhancement and soil conservation policies necessary for the achievement of sustainable agricultural development.

Unlike the depreciation of manufactured assets, the effects of soil degradation (declining soil fertility) are not reflected in conventional measures of economic welfare in order for policy makers to understand the long-term dangers of the problem (Magrath and Arens, 1989). This occurs because markets seldom exist for soil resources, due to the pervasive influence of externalities on the true costs of soil erosion, and because systems of national economic accounts treat natural resources as free goods. Literature on the economic costs of soil degradation is limited. So far, only one study was carried out in Malawi that has tried to measure economic costs of soil erosion (Bishop, 1992). However, this study is based on a static formulation and stopped short of providing adequate analysis of the long-term and dynamic consequences of the depletion of soil resources on agricultural productivity and social well being of the people of Malawi.

According to Barbier (1986), land quality is classified as a slowly renewable resource. When the major reason for land degradation is nutrient loss (nutrient mining through crop harvest), soil quality can easily be restored through supply of external inputs such as manure and inorganic fertilizers. In other words, net-extraction of nutrients or soil mining can occur and drastically affect land productivity without posing an irreversible long-run threat to land productivity since measures are available not only to arrest, but also to compensate for nutrient losses ex-post (Brekke et. al., 1999). However, the destruction of soil physical structures and rooting depth as a result of erosion of the topsoil causes an irreversible long-term damage to land productivity. Unfortunately, such distinction is lacking in the study carried out by Bishop (1992) on Malawi. This current study focuses on the problem of soil degradation as a result of soil erosion and soil-mining. An inter-temporal optimisation framework is utilised to determine an optimal extraction path of the soil nutrient stock.

While the main thrust of this study is measuring the dynamic costs of soil degradation (soil-mining), attention is also given to improving our understanding of the problem of adoption of soil conservation practices among smallholder farmers in Malawi. As pointed out earlier, controlling soil erosion is extremely important in reducing the loss of nutrients adsorbed on fine particles (Pieri, 1995). Considering the poverty situation in Malawi, soil conservation is assumed to be the most appropriate and affordable intervention for smallholder farmers in order to limit the damage caused by soil erosion. However, such intervention is currently hampered by the low adoption among smallholder farmers of soil conservation technologies. Although some significant contributions have been made towards understanding this problem (Mangisoni, 1999), no research work has focused on understanding the decision making process of the smallholder farmers when adopting any technology. This study is, therefore, designed to contribute to the improvement of existing knowledge on the key factors influencing adoption of soil conservation technologies. The study separates factors influencing the incidence and the extent of adoption of soil conservation technologies among smallholder farmers in Malawi. Such an approach is assumed vital not only for the formulation of strategic policies that would boost adoption of those technologies, but importantly, the actual designing of appropriate small-scale soil conservation technologies.

1.2 Objectives of the Study

The primary objectives in this study are to measure the dynamic costs of soil degradation (soil erosion and soil-mining) and determine factors influencing the incidence and extent of adoption of soil conservation technologies among smallholder farmers in Malawi.

The following are the specific objectives:

- to calculate dynamic user costs of soil quality (soil nutrient stock)
- to determine the steady state (SS) optimal path for soil nutrient stock and optimal rate of replenishment from external sources (e.g., SS optimal rate of commercial fertilizer application)
- to calculate user cost as percentage of gross domestic product in order to come up with a better measure of national wealth.
- to determine key factors that influence farmers' decision on incidence and extent of adoption of soil conservation practices in Malawi.
- to analyse policy implications and come up with relevant policy recommendations

1.3 Approaches and Methods of the Study

As already pointed out, this study has two main objectives: to measure the dynamic costs of soil degradation and, to determine factors that influence the incidence and extent of adoption of soil conservation technologies among smallholder farmers. As such, two main analytical tools are employed to achieve the objectives stated above.

First, considering that soil degradation (soil erosion) has long-term consequences, this study adopts an inter-temporal framework combining scientific models of crop productivity and soil degradation (see Aune and Lal, 1995). In this framework, smallholder farmers choose optimal levels of labour, capital and external inputs in order to maximize stream of net benefits over time as a dynamic optimisation decision problem.

Second, factors influencing incidence and extent of adoption of soil conservation technologies in Malawi are analysed using a selective tobit model. This model simulates a two-step decision-making process of smallholder farmers when deciding adoption. This approach was adopted in order to deepen our understanding of the way smallholder farmers make decisions concerning adoption with the hope to try explain the main reasons behind the low adoption of soil conservation technologies in Malawi.

1.4 Organization of the Thesis

The following chapter gives a brief background on the importance of agriculture to the economy, describes the physical and chemical characteristics of the soils of Malawi and also, examines some evidence of declining trend of soil fertility in Malawi. Chapter III presents a review of literature on some models that have been used to predict soil erosion and crop productivity. Literature on the theoretical development of erosion economic analyses and the various approaches that have been used to measure the soil economic costs of soil erosion are also presented in this chapter. Chapter IV presents the analytical inter-temporal optimisation framework and discusses analytical results for the optimal control model of the soil-mining problem under study. Chapter V applies the dynamic optimisation model described in chapter IV to the soil-mining problem in Malawi. The specified model is used to solve the soil-mining problem among smallholder maize farmers in Malawi. Empirical estimation of the specified model parameters is performed in this chapter. Data sources and econometric procedures used for estimation of the model parameters are also discussed. Chapter VI presents a selective tobit model used to determine factors influencing incidence and extent of adoption of soil conservation technologies among smallholder farmers in Malawi. Chapter VII presents empirical results and discussion of the selective tobit model. Finally, chapter VIII presents general summary, conclusion and policy implications based on the dynamic optimisation model and also, results of the selective tobit analysis of adoption of soil conservation practices.

CHAPTER II

AGRICULTURE AND SOIL RESOURCES OF MALAWI

2.1 Agricultural Sector in Malawi

Malawi lacks the mineral resource endowments of its neighbouring countries (Zambia, Mozambique and Tanzania). Agricultural land therefore, constitutes the primary natural resource for the Malawi economy. Agriculture in Malawi is characterized by a degree of dualism that has dichotomised the sector into smallholder and estate sub-sectors (Mkandawire et al, 1990). The dichotomy is essentially reflected in the tenurial systems under which land is cultivated. Smallholder agricultural production is predominantly on customary land. Under this system, land is the property of the community with individual user rights. Under customary land system, chiefs and village headmen are the custodians of land. Smallholder farmers usually have small, scattered and usually fragmented lands emanating mostly from population pressure and other socio-economic factors. The smallholder sub-sector is the backbone of Malawian agriculture occupying about two thirds (1.98 million hectares) of the total harvested agricultural land (FAO, 1998). Maize is the main crop grown under this predominantly subsistence farming system. This crop alone comprises 75 per cent of the total smallholder agricultural land in Malawi (Barbier and Burgess, 1992a). Other major subsistence crops include cassava, sorghum and sweet potatoes. Smallholder farmers also grow a number of cash crops such as burley tobacco, grain legumes (beans and groundnuts), cotton, coffee and spices.

Estate production occurs mainly on leasehold or freehold land. Estates are exclusively involved in cash crop production. Main cash crops are tobacco (dominant export crop), tea, coffee, sugarcane and macadamia nuts.

Agriculture accounts for over 80 per cent of Malawi's export revenue predominantly from tobacco, tea, sugar, and coffee (Figure 1). On average the agricultural sector contributes about 34 per cent of the GDP (Table 1). By 2001, the total labour force in

Malawi was about 4.5 million and almost 84 per cent of this is engaged in agriculture (Table 2). Over 90 per cent of the population engaged in agriculture live in rural areas (Table 2). The slow growth of the manufacturing sector in Malawi means that the agricultural sector will continue to shoulder the burden of providing a livelihood for a large proportion of the country's growing population. It is not surprising therefore, that policy action for Malawi, both agricultural and economy-wide, has largely been based on influencing the dynamism of the agricultural sector.

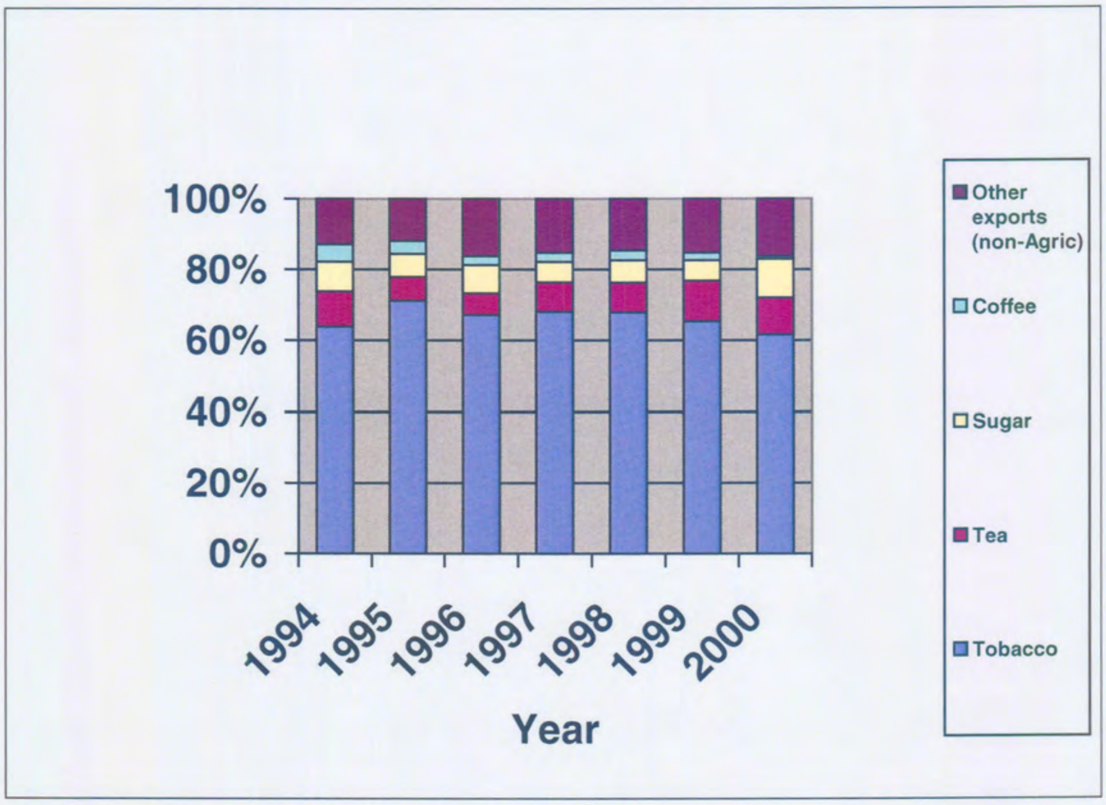

Figure 1: Principle domestic exports for Malawi %: 1994-2000

Source: MNEC (2001)

Table 1: Gross Domestic Product by Sector of Origin at 1994 Factor Price (MK million)

Sector	1994	1995	1996	1997	1998	1999	2000	2001
Agriculture	2,319	3,238	4,064	4,069	4,490	4,944	5,210	5,365
Smallholder	1,624	2,332	3,070	2,964	3,520	3,992	4,059	4,265
Estate	695	906	993	1,105	969	951	1,151	1,100
Mining/quarying	43	47	206	157	164	170	188	210
Manufacturing	1597	1,685	1,675	1,691	1,717	1,749	1,705	1,690
Electricity/ water	149	152	152	161	172	172	189	198
Construction	202	198	231	254	266	293	288	281
Distribution	2537	2576	2575	3,018	2,838	2,765	2,760	2939
Transport &communication	465	550	505	553	559	576	552	580
Financial& professional services	627	691	834	1,128	1034	1,032	1,057	1253
Ownership of dwellings	162	165	169	172	176	180	185	189
Private &social and services	211	215	237	260	262	264	271	279
Producers of govt services	1114	1,198	1,168	1,200	1,232	1,257	1,282	1,297
Unallocatable financial services	-278	-305	-317	-361	-344	-378	-387	-456
GDP factor cost	9,149	10,411	11,498	12,303	12,568	13,023	13,300	13,601
Agric % of GDP	25.34	31.1	35.3	33.07	35.7	39.9	39.17	39.4
Average Agric % of GDP								34.87

Source: MNEC (2001)

Table 2: Economically active persons by industry in Malawi

Industry	Malawi Total	Urban	Rural
Total working	4,458,929	456,084	4,002,845
Agriculture and forestry	3,724,695	90,360	3,634,335
Fishing	41,132	1,754	39,378
Mining and Quarrying	2,499	686	1813
Manufacturing	118,483	42,205	73,278
Electricity, gas and water	7,319	5,261	2,058
Construction	73,402	37,158	36,244
Wholesale and retail trade	257,389	128,502	128,887
Hotels and restaurants	15,303	8,913	6,390
Transport, storage and communication	32,623	24,334	8,289
Finance and insurance	5,099	4,672	427
Real estate and business activities	8,858	6,517	2,341
Public Administration	101,433	75,333	26,100
Community and Social Services	136,357	62,019	74,338
Education	79,572	30,051	49,701
Health and social work	31,931	16,812	15,119
Other community services	24,674	15,156	9,518

Source: National Statistic Office (NSO) (1998) population census results.

Agricultural growth is a catalyst for broad-based economic growth in most developing and low-income countries (Pinstrup-Andersen and Pandya-Lorch, 1995). Agriculture's links to non-farm sectors generate considerable employment, income, and growth in the rest of the economy. Globally, very few countries have experienced rapid economic growth without agricultural growth either preceding or accompanying it. Although diversification out of agriculture may occur in the long-term, in the short-term many developing nations lack alternatives. While the average annual growth rate for agriculture in the low and middle income developing countries slowed down in the first half of the 1990s to 2.0 per cent compared to 3.1 per cent in 1980s, in Sub-Saharan Africa, the growth rate was lower and falling from 1.9 per cent in 1980-90 to 1.5 per cent in 1990-95 (World Bank, 1997). Admittedly, annual percentage growth rate for agricultural GDP in Malawi has been declining and so is the overall annual percentage growth rate for GDP at factor cost (Figure 2). The decline in annual percentage growth rate for agriculture is mainly attributed to the falling tobacco output and exports resulting from limited access to credit by farmers for the procurement of inputs, falling auction prices for tobacco and importantly also, effects of drought [MNEC,1999; 2000]. Falling smallholder maize output in recent years has also contributed to this decline.

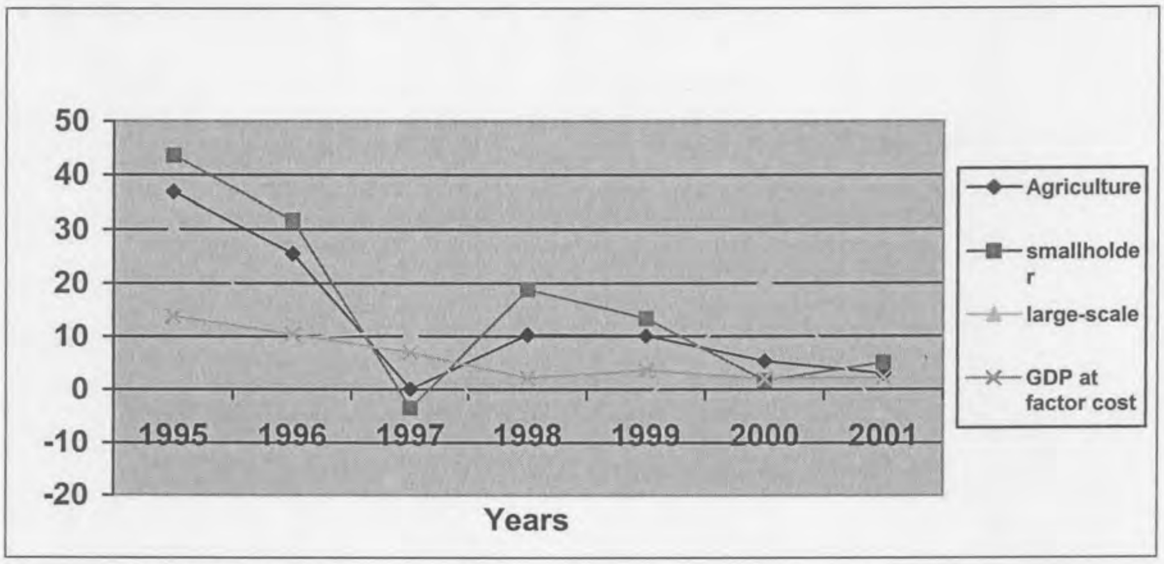

Figure 2: GDP by agricultural sub-sector at 1994 factor cost: Annual percentage growth rate(1995-2001)

Source: Data adapted from MNEC (2002)

Productivity of smallholder agriculture in Malawi has stagnated or decreased over the years. Maize yields between 1985 and 2000 fluctuated a lot in all the eight agricultural development divisions (ADD[1]). A lot of factors contributed to this fluctuation. However, erratic rainfall, drought, and limited credit and capital by farmers for the procurement of inputs were the major causes. Noteworthy, there is an overall declining trend in maize yields observed in all the ADDs (Figure 3). Coupled with a growing population, an obvious implication of the falling maize output over the years has been, to certain extent, a declining trend of per capita kilogram (kg) maize equivalent in the country (Figure 4). The declining per capita kilogram maize equivalent has serious implications on food security, especially among the rural poor households. Most of the rural poor households do not have adequate purchasing power to buy and supplement their maize food reserves in the event of poor harvest.

It is asserted that increase in agricultural production in Malawi has over the years resulted from land expansion rather than increase in productivity. In 1946, over half the land in Malawi (five million hectares) was forested (Orr et al., 1998). However, by 1991, analysis of satellite images revealed that the forested area had decreased by 50 per cent, down to 2.5 million hectares, or only 27 per cent of the country's land area. Of this forested area, 1.3 million hectares are found within protected area boundaries. In other words, 53 per cent of Malawi's current natural woodland lies within reserves and parks. The decline, associated exclusively with agricultural clearing over the past fifty years, has come at a rate of 1.5 per cent per annum (Orr et. al, 1998). Opening more land to agricultural production entails more erosion of the soils. Hence, curtailing soil degradation and improving soil productivity would be a way forward if the country is to achieve sustainable agricultural development.

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[1] Malawi is divided into eight agricultural development divisions (ADD). Blantyre ADD (BLADD), Shire Valley ADD (SVADD) and Machinga ADD (MADD) in the Southern region; Lilongwe ADD (LADD), Salima ADD (SLADD) and Kasungu ADD (KADD) in the Central region and finally, Mzuzu ADD (MZADD) and Karonga ADD (KRADD) in Northern region.

Obviously, the fast growing population in Malawi puts more pressure on agricultural land. Population pressure on public land is greatest in the south and central regions of Malawi, with population densities of about 100 people per km^2 in the 1987 census. Current land holding size is estimated to be one hectare per family. Estimated average family size in Malawi is 5 persons, implying a land holding size of 0.2ha per person. Estimates by FAO (1986) indicated that Malawi had the least cropland per capita in 1980s, 0.42 ha, compared to its neighbours; Tanzania, Zambia, and Zimbabwe, with per capita land of 0.48 ha, 0.95ha and 0.56 ha, respectively. Projected cropland demand for 2010 for Malawi, Tanzania, Zambia and Zimbabwe was 0.2 ha, 0.29 ha, 0.49ha and 0.25ha, respectively. The projected reserve of potential cultivable land for 2010 for Malawi, Tanzania, Zambia and Zimbabwe is 0.06ha, 0.36ha, 2.83ha and 0.49 ha, respectively. It is evident that Malawi faces an acute land shortage and the picture is particularly gloomy when we consider the low application of external inputs among smallholder farmers.

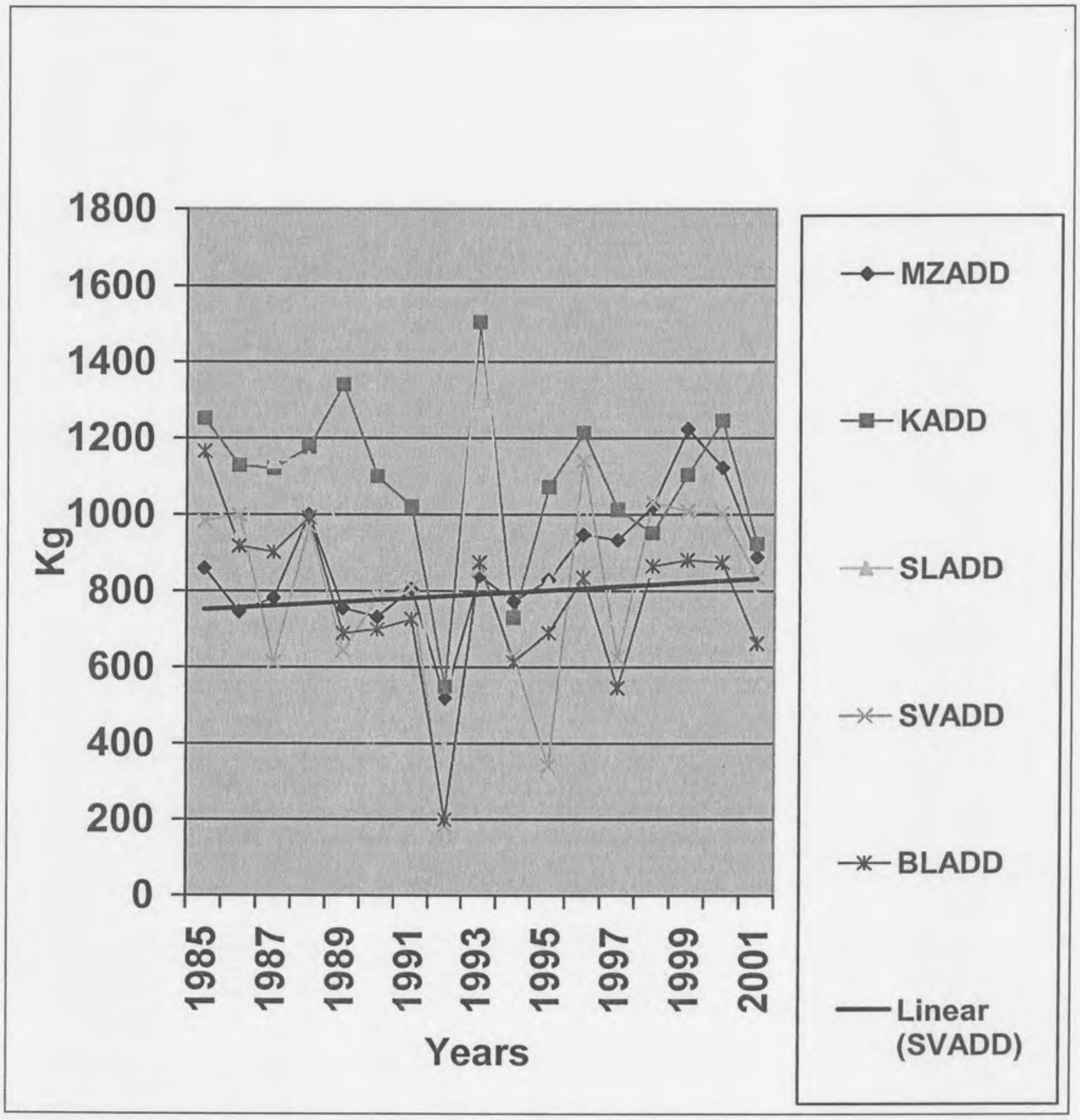

Figure 3: Smallholder Maize Yield Trend in Malawi: 1985-2001

Source: Data adapted from MNEC (2002)

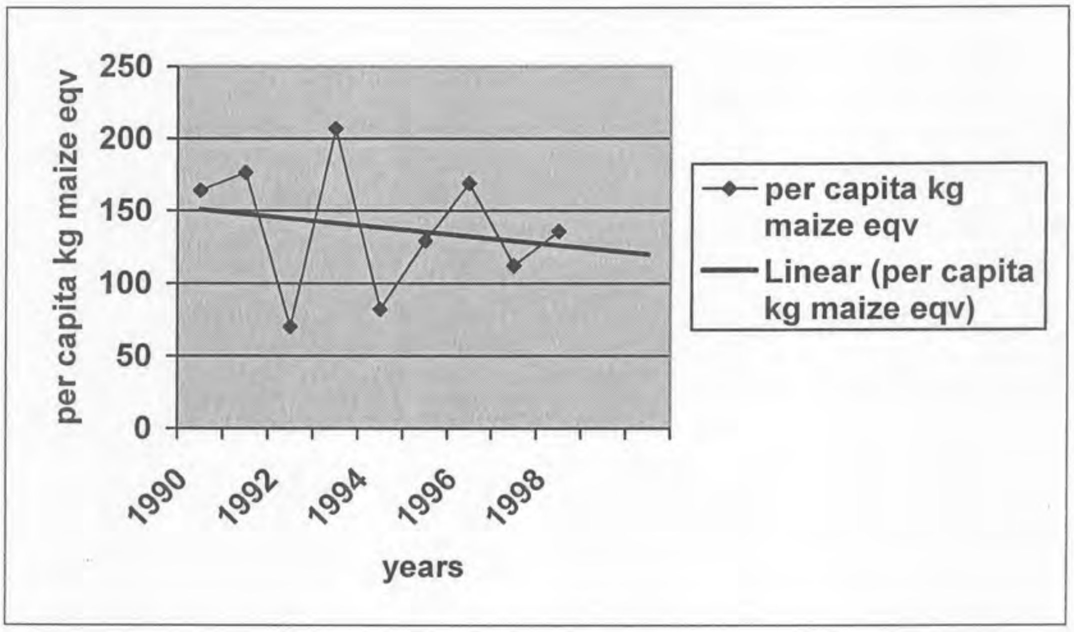

Figure 4: Per capita kg maize equivalent for Malawi: 1990-1998

Source: Data adapted from MoAI (2000)

Worse still, only little proceeds from agriculture have been ploughed back into this sector. The FAO (1996c) has indicated that investments in agriculture declined in Malawi and other Sub-Saharan countries in recent years. The limited budget allocated to the agricultural sector has resulted in some important public institutions of the sector such as research and extension services being under funded (MNEC, 2001). Importantly, the slow agricultural growth and the lack of adequate investment in this sector have been accompanied by rapid degradation of the natural resource base (Oldeman, 1990). Renewable resources, which comprise the environmental base for agriculture and most other economic activities in rural areas, are under threat. However, the threat of soil erosion is extremely high among smallholder farms due to low fertility and fragility of the soils. Nutrients in the tropical soils often concentrate only in the top few inches of the topsoil, making the soils subject to nutrient depletion and other adverse effects from soil erosion [Lal, 1987, 1988]. Unless right policies are put in place to manage and improve the productivity of the soils in a sustainable manner, declining fertility of the soils will seriously undermine benefits of any modern agricultural production techniques.

2.2 Food Security Situation in Malawi

Food security situation in Malawi has worsened over the years. Of late, Malawi has been supplementing its domestic maize production with imports from South Africa and other neighbouring countries. For example, in 1997/98 growing season, the country experienced a maize shortage of 53,942 tons. In 1998/99 growing season, Malawi imported about 181,524 tons of maize and planned to import at least 80,000 tons in 2000 (MNEC, 1999). Declining soil fertility coupled with low application of external inputs such as commercial fertilisers, drought and floods are the main reasons behind the low agricultural production in Malawi.

2.2.1 Agricultural support programs

In order to assist boost smallholder production, the government and the donor community embarked on various support programs. For example, the Starter Pack Program is a Malawi Government and Donor Community (British Government, European Union and World Bank) initiative that envisaged free distribution of suitable cereal and legume seeds among farm families in the country. In addition to the free seed, 15kg of fertilizer was also supplied to each farmer for free. The package supplied was estimated to be enough for 0.25 ha of land. In 1998/99 growing season, a total of 2,524,264 farm families benefited from this program. However, this program is now known today as Targeted Input Program (TIP). Thus the targeted clientele is now the very poor farmers and this has significantly reduced the number of potential beneficiaries.

Another support program aiming to boost smallholder farm productivity is the Agricultural Productivity Investment Program (APIP). This program is supported by the European Union. The program provides hybrid maize seed and fertilizer to resource poor farmers. This is achieved through the provision of credit guarantees to private tenders to buy fertilizer and seed to distribute to farmers. In 1998/99 growing season, about 255,200 farmers received farm inputs from this program [MNEC, 1999; 2000].

2.3 Existing Policy Framework

2.3.1 Agricultural pricing policies and land degradation

Government intervention in agricultural markets can have significant impacts on farm-level incentives for soil management (Barrett, 1989). Government regulations, which artificially suppress producer prices, create a disincentive to invest in land husbandry (Repetto, 1988). Domestic agricultural pricing policies that until 1994/1995 biased against smallholder producers can thus partly be blamed for the persistent soil erosion and soil mining common on smallholder land in Malawi. The government through its marketing board, the Agricultural Development Marketing Corporation (ADMARC) charged implicit tax on all smallholder commodities. This provided no incentive to smallholder farmers to make investment on the land that provided for them. It is not surprising therefore, that most of them only produced for subsistence. Liberalization of input and output markets was done simultaneously in 1994/95 under the auspices of the structural adjustment program. The output market liberalization was aimed at altering incentives towards producers with regard to pricing and marketing of outputs. However, the participation of private traders in the produce market has been seriously constrained by limited access to credit and capital. The Agricultural Development and Marketing Corporation (ADMARC[2]) has, therefore, continued not only to be the major buyer of smallholder produce, but also to, influence producer prices as well (Nakhumwa and Hassan, 1999). Even after market liberalization, producer prices for most of the smallholder crops in Malawi are still low due to lack of competition. Private traders

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[2] Agricultural Development and Marketing Corporation (ADMARC), is the government marketing board.

operating in rural areas, unable to bear the losses which ADMARC absorbed, offer producer prices 20-30 per cent below the official floor price, which narrows the profit margin for maize (Carr, 1997). Noteworthy, input market liberalization in 1994/95, therefore complete removal of input subsidies, coincided with the floatation of the local currency (Malawian Kwacha). The sequential devaluation of the Kwacha and the rising fuel prices inflated input prices beyond the means of most smallholder farmers (Ng'ong'ola et al., 1997). The low producer prices offered to smallholder farmers often times do not offset the high cost of production faced by farmers due to the high cost of mineral inputs. Consequently, a lot of smallholder farmers stick to their traditional way of production since modern agriculture, under the prescribed conditions, is not profitable for most of them.

Prices affect farmers' decisions regarding land husbandry in four ways (Barbier and Burgess, 1992b):

- influences the level of agricultural production;
- incentives to invest in future production;
- changes in crop mixes through relative price changes and;
- effects on price variability (to what extent farmers can reliably predict future prices).

However, impact of price change cannot be generalized because of its contradictory effects (Barbier, 1988a). While an increase in the output price creates an incentive for increased soil erosion in the current period (to increase production and profits—Lipton, 1987), the price increase if it is permanent, also increases returns to future production and thus creates an incentive to conserve more soil for future use (Repetto, 1988). By increasing the profitability of agriculture, a price increase will lead farmers to use more inputs and increase agricultural output through intensification or cultivating more land. Using more non-conservation inputs will tend to increase rate of soil erosion, assuming that production increases can only be achieved in the short-term at the expense of increased soil erosion. But the increase in profitability will also create an incentive to conserve soil as an agricultural "input", implying greater soil depth and less soil erosion

(Eaton, 1996). However, smallholder farmers in Malawi are currently faced with exorbitant input prices and low producer price making agriculture unprofitable. In other words, smallholder farmers have no incentives to conserve the soil, the very resource that spells their survival.

Also, changes in agricultural prices will effect land degradation indirectly by altering the crop mix grown by farmers (Barbier and Burgess, 1992b). Certain crops can be characterized as leading to more soil erosion under conventional methods of cultivation than others [Barbier, 1991; Barrett, 1989]. Barbier (1991) examined cropping patterns in Malawi over the period 1969-1988 to see if there is any correlation with observed shifts in relative gross margins. However, the evidence was sparse. Another way in which agriculture pricing can affect land management is through price variability (Barbier and Burgess, 1992b). If relative prices and returns from different cropping systems fluctuate significantly then one might expect farmers, particularly smallholders, to be less likely to switch between systems given the high degree of risk involved. Barbier (1991) examined the variability of non-erosive to erosive crop price ratio in Malawi over the same period and found that farmers face a high degree of price risk "which could have important influence on the incentives for improved land management". Due to the high volatility of agricultural prices, many smallholder farmers in Malawi consider production of maize first (staple food), although it is an erosive crop.

2.3.2 Soil fertility policy

Before independence in 1964, the colonial government in the then Nyasaland (Malawi) put soil conservation and soil fertility high on the agricultural agenda. In many instances coercive methods were used to enforce soil conservation measures among the indigenous people [Wellard, 1996; Mangisoni, 1999]. Immediately after independence, soil conservation was put at the peripheral, as it was associated with colonialism. However, increased attention to soils was evidenced again during the 1980s and early 1990s through the government and donor partnership. Such initiatives, however, did not emphasize on soil fertility *per se*. In 1995, the Ministry of Agriculture and Livestock Development, for the first time, highlighted the need to tackle the land degradation problem (NRI, 1998). The policy objective was stated as "prevention of degradation and restoration of soil fertility". The strategy to attain the policy included the following:

- Developing and promoting economically viable and sustainable farming systems;
- Encourage watershed management as an integral part of targeted intervention for the resource poor;
- Publicizing security and vulnerability of the natural resources.

The government's current agricultural development, environment and poverty alleviation policies address soil fertility degradation as a major issue. The Agricultural and Livestock Development Strategy and Action Plan (ALDSAP) priorities for resource-poor rural households are:

- Restoration and maintenance of soil fertility
- Conservation of natural resources
- Improve food security
- Promotion of income-earning opportunities
- Gender issues to be explicitly incorporated in the development process

The National Environment Action Plan (NEAP) identifies soil erosion as the biggest threat to sustainable agricultural production and as a major source of water resources contamination. Urgent attention is required to arrest soil degradation. In 1996, a Land Use Policy and Management Action Plan was prepared with support from FAO and UNDP but was never implemented. The Government of Malawi commissioned three studies on land use and tenure. The output, is hoped, may lead to policy recommendation for consideration by the Presidential Land Commission of Enquiry.

2.4 Malawi Soil Resource

Soil is a primary natural resource base for agriculture. It has been argued that enhancement of soil productivity is essential to the sustainability of agriculture and to meeting basic food needs of the rising population in Malawi. Bearing in mind the enormous pressure on land due to the rapidly growing population in Malawi and the imbalanced extraction and application of nutrients in the smallholder sub-sector, it is believed that the quality of agricultural land in Malawi is steadily declining.

This section presents the distribution of major soils of Malawi according to ADDs (Map 1). Physical and chemical characteristics of the major soils are also presented to indicate the fertility status of the soils. Map 2 shows the distribution and levels (%) of nitrogen (N), the most important nutrient for crop production in Malawi. Importantly, a trend of Soil Organic Matter (SOM) is established from research data for the 1970s and 1990s. Such trend is worthwhile as it shows what is happening to the nutrient stock of Malawi soils. Declining SOM typically results in soils with lower nutrient holding capacities and lower levels of available plant nutrients. Findings of the SOM trend are augmented by research data on maize response to nitrogen over a period of time. Soil nutrient balances for the major nutrients have also been incorporated to indicate the way the current farming systems are utilizing and managing the soil resource.

2.5 The Major Soils of Malawi

Soils in Malawi are broadly divided in two groups, namely (a) the residual (upland) soils and (b) alluvial soils. Each of these broad groups can be further divided into subgroups. The 13 major subgroups are grouped using the FAO classfication and are spread throughout the country (Figure 5). Some of these soils have been described below.

Ferralsols, also known as Oxisols (soil taxonomy) or Ferrallitic soils (Malawi classification system), are widely prevalent in Malawi and include, Xanthic Ferralsols (orthox in soil taxonomy). These soils are normally deep but others are shallow. Xanthic Ferralsols soils are moderately acidic to acid (pH 5.5-5.7). Both nitrogen (0.05-0.12%) and organic matter (0.4-1.6%) are very low to low. Available phosphorous (P) ranges from trace to medium (0-22ppm) and potassium ranges from low to medium (0.11-0.36 cmols/kg soil). Levels of organic carbon and nitrogen indicate rather poor soil fertility status. The other key elements (P and K) are lacking as well.

However, the most productive upland soils in Malawi are the Ferric Luvisols, commonly known as ferruginous soils or Ferric Rhodustalf (soil taxonomy). These soils have moderate to strong structures and are normally deep except on dissected sites. Ferric luvisols are acidic to almost neutral (pH5.3-6.7), and base saturation is moderate to high (60-90%). The cation exchange capacity (CEC) is low to moderate (5.44-8.5 cmols/kg soil). Organic matter is low to high (0.5-4.5%) while nitrogen is low to medium (0.04-0.2%). Available phosphorous is trace to medium (0-24ppm). Levels of both organic matter and nitrogen content clearly indicate that these are not rich soils.

Prevalent in high rainfall areas of the country are Dystric Nitosols, also known as Paleustult (soil taxonomy) or Ferrisols (Malawi classification). These soils have high CEC and are highly weathered. They are usually very deep soils (>150cm), well drained with dark or red colour and clay texture throughout the profile. For most of the soils in this group, aluminium toxicity is the major limiting factor to sustainable crop production. In such soils, phosphorous is also limiting because either the high aluminium and iron oxides fix P, or P may just be inherently deficient. Most of these soils have low potassium (K), typical examples being Bembeke series, Thyolo, Mulanje, Chikangawa and some parts of Nkhatabay district. Dystric Nitosols are strongly acid (pH 4.3-5.0) and base saturation ranges from very low to low (17-19%). CEC is very low (1.97-2.73 cmols/kg soil). The organic matter is medium to high (1.7-4.6%), and nitrogen ranges from low to high (0.08-0.23%). Available P is low to moderately high (10-33ppm). Potassium, magnesium and calcium are very low. Tables [3a-c and 4] present detailed physical and chemical analyses for major soils in Malawi.

2.5.1 Physical and chemical properties of Malawi soils

Sanchez and Palm (1996) define nutrient capital as the stocks of nitrogen (N), phosphorous (P) and any other essential elements in the soil that become available to plants during a time scale of 5 to 10 years. It is reported that nitrogen and phosphorous, in that order, are the two most limiting nutrients to food production in Africa [Ssali et al., 1986; Woomer and Muchena, 1996; Bekunda et al., 1997]. Physical and chemical properties of the soil, portrays a picture concerning the fertility status of the soils. Nutrient capital may be expressed as kilograms per ha of N or P within the rooting depth of plants.

Using survey data and secondary data, physical and chemical properties of soils for the ADDs (Tables 3a-3c), are reported. All physical and chemical properties of soils at ADD level were based on reports from the department of Land Resources (under Ministry of Agriculture and Livestock Development). Noteworthy, these reports were compiled in 1991 and therefore, caution should be taken when interpreting the results for the ADDs. Since some time has elapsed, it is more likely that the levels of nitrogen and phosphorous could even be lower bearing in mind the following characteristics of smallholder farmers in Malawi: (1) poor use of external inputs such as inorganic or organic fertilizers, coupled with; (2) continuous cultivation of maize on same pieces of land; and (3) low adoption of soil conservation technologies. Figure 6, presents the distribution and levels (%) of nitrogen, a key soil nutrient for crop production in Malawi. Most soils in Malawi have low levels of nitrogen [Figure 6; Table 3a-c] meaning that the soils cannot adequately support crop production without supplementation of key nutrients such as N and P from external sources. More recent data depicting soil physical and chemical characteristics of the soils were calculated using survey data for Nkhatabay and Mangochi districts (Table 4).

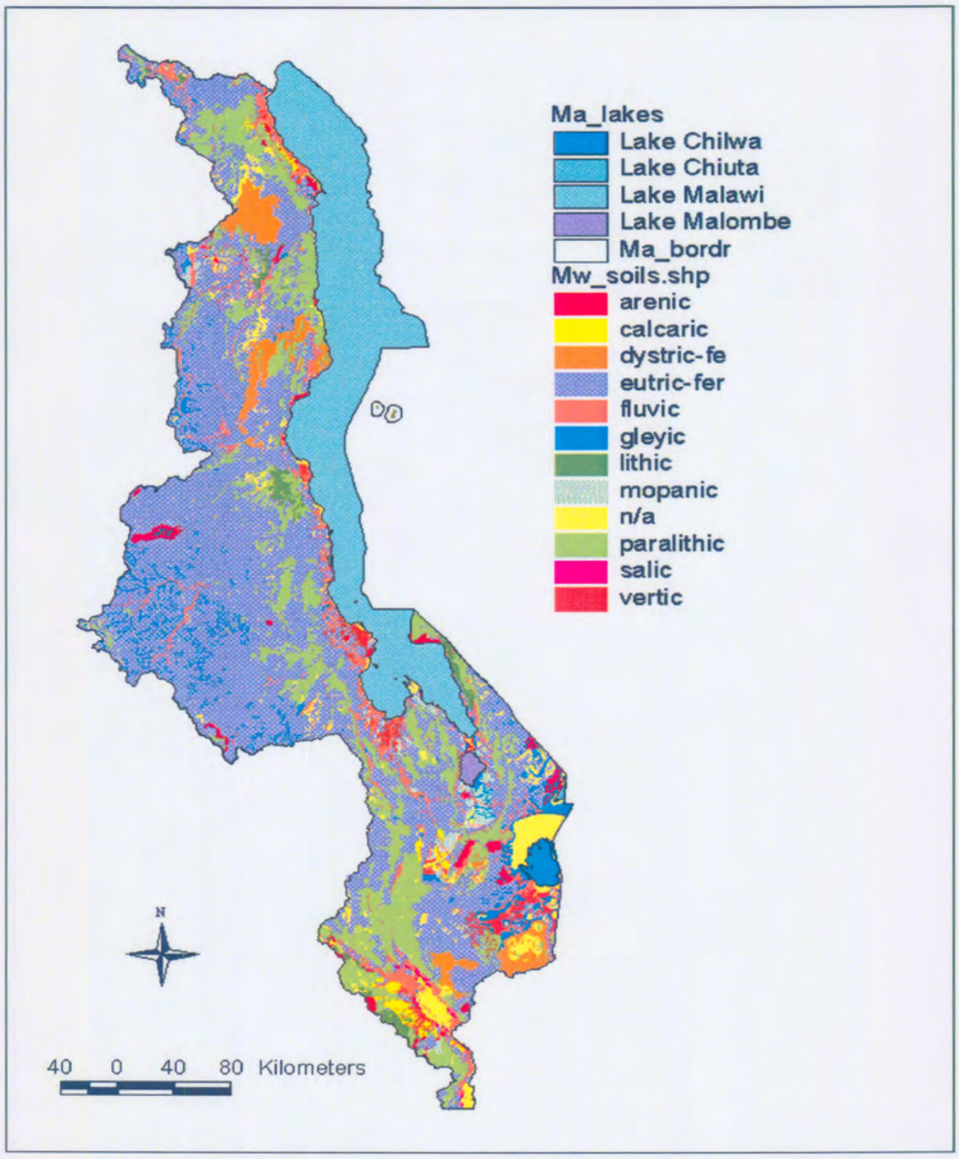

Figure 5: Distribution of Major Soil Groups in Malawi

Source: Mkandawire 2001 (data adapted from dept. of Land Resource, 1991)

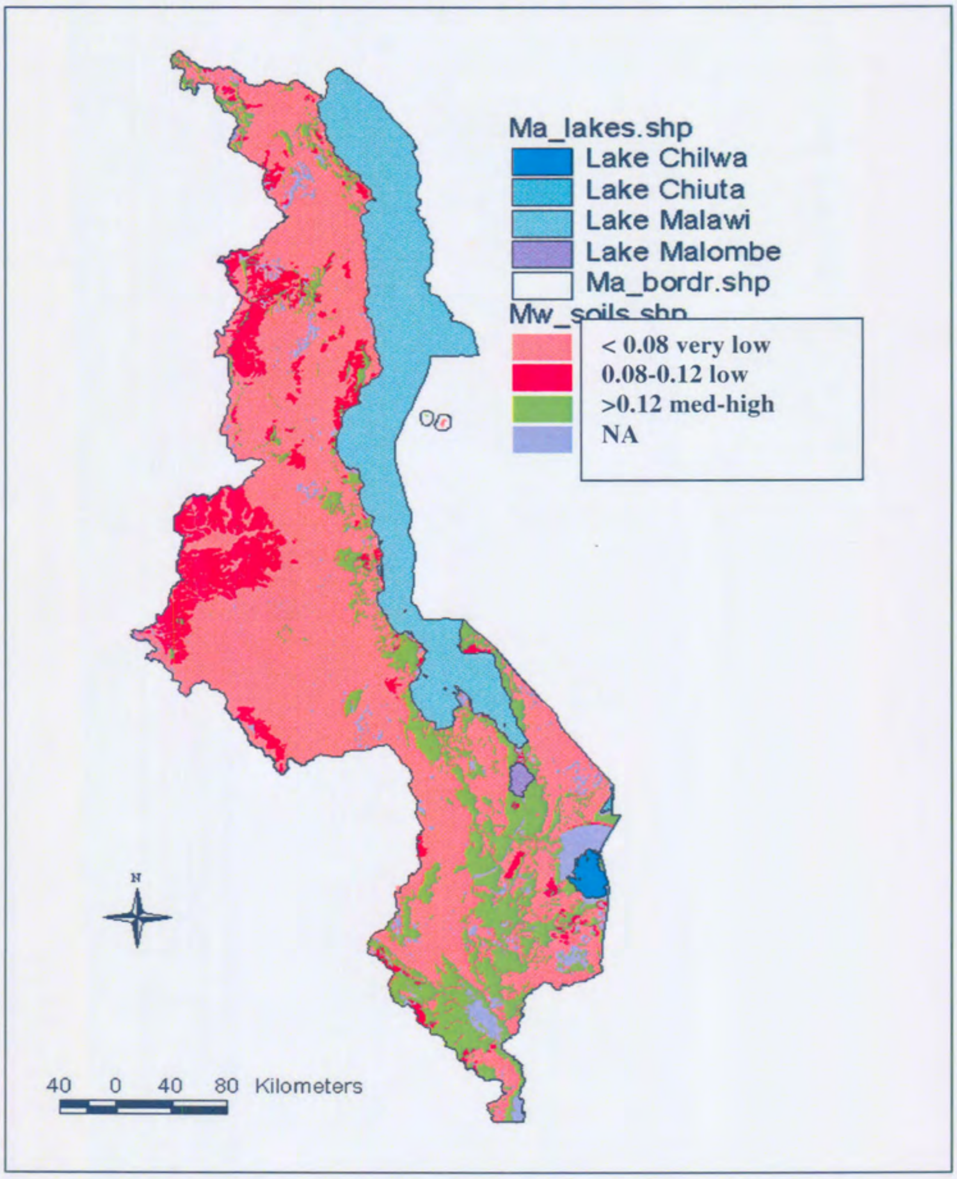

Figure 6: Distribution of Nitrogen (%) in Malawi Soils

Source: Mkandawire 2001 (data adapted from dept. of Land Resource, 1991)

Table 3 (a): Classification, physical and chemical properties of soils in the Northern Region of Malawi

Area ADD	Agro-ecological zone	FAO (1988) soil classfication.	Soil depth (cm)	Particle size (0-30cm)	Soil Chemical Properties (0-50cm)				
					pH	CEC[3]	N%	P (ppm)	K me/100g
KRADD[4]	Karonga (KA) Lakeshore plain	Vertic Cambisols	>150 very deep	Sandy clay to clay	5.5-6.5	>10 med-very high	<0.08 very low	<6 very low	>0.2 med-very high
	KA lakeshore, escarpment east	Haplic luvisol Eutric cambis	>150	Loamy sand to sandloam	5.5-6.5	5-10 low	<0.08 very low	<6 very low	0.1-0.2 low
	KA escarpment (E+C), Kyungu lowlands	Eutric and Haplic phaeozems	50-100 mod. deep	Loam sand to sand clay loam	5.5-7.0	5-10 low	>0.12med-very high	6-18 low	>0.2 med-very high
	KA escarpment, Misuku hills	Haplic lixisols	50-100	Sandy loam to clay	5.5-6.5	5-10 low	0.08-0.12 low	<6 very low	>0.2 med-very high
MZADD	Rumphi,Nkhata Mzimba (N+E):	Haplic lixisols	50-100	Sandy loam to clay	5.5-6.5	5-10 low	0.08-0.12 low	<6 very low	>0.2 med-very high
	Viphya	Haplic lixisols (Eutric Ferralic)	>150	Sandy clay loam to clay	5.0-6.0	5-10 low	<0.08 very low	<6 very low	>0.2 med-very high
	Nyika plateau	Haplic Acrisols	100-150 deep	Sandy clay loam	4.5-5.5	5-10 low	0.08-0.12 low	<6 very low	>0.2 med-very high

Source: MoA (1991)

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[3] CEC=cation exchange capacity; ppm=parts per million; me=milequivalent; P=phosphorous; K= potassium

[4] Karonga Agricultural Development Division (ADD) and Mzuzu ADD

Table 3 (b): Classification, physical and chemical properties of soils in the Central Region of Malawi

Area ADD	Agro-ecological zone	FAO (1988) soil classific.	Soil depth (cm)	Particle size (0-30cm)	Soil Chemical Properties (0-50cm)				
					pH	CEC	N%	P (ppm)	Kme /100g
LADD[5]	Dedza and Ntcheu Escarp	Eutric, Chromic Cambisols	50-100	Loam sand-sandy loam	5.5-6.5	5-10 Low	0.08-0.12 Low	<6 very low	>0.2 med-very high
	Ntcheu+Golomoti foot-slopes	Eutric Fluvisols	>150	Loamy sand to sand clay loam	5.0-6.5	5-10 Low	<0.08 very low	<0.6 very low	>0.2 med-very high
	Dzalanyama hill	Eutric cambisols	100-150	Loamy sand -sand loam	5.5-6.5	5-10 Low	<0.08 very low	<0.6 very low	>0.2med - very high
SLADD[6]	Nkhotakota, Dwangwa lowlands	Haplic & Chromic Luvisols	>150	Sand to sandy loam	5.5-6.5	5-10 low	<0.08 very low	<6 very low	>0.2 med-very high

Source: MoA (1991)

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[5] LADD is Lilongwe Agricultural Development Division

[6] SLADD is Salima Agricultural Development Division

Table 3 (c): Classification, physical and chemical properties of soils in the Southern Region of Malawi

Area ADD	Agro-ecological zone	Soil classification FAO (1988)	Soil depth (cm)	Particle size (0-30cm)	Soil Chemical Properties (0-50cm)				
					pH	CEC	N%	P (ppm)	Kme /100g
MADD[7]	Upper Shire Valley-Machinga	Eutric Fluvisols	>150	Sandy clay loam	5.5-6.5	>10 med-very high	0.08-0.12 low	6-18 low	>0.2 med-very high
	Chilwa and Chiuta lowlands	Eutric Fluvisols	>150	Loamy sand to SCL	5.0-6.5	5-10 low	<0.08 very low	<6 very low	
	Makanjila lakeshore plains	Cambic Arenosols	>150	Sand to loamy sand	6.0-7.0	<5 very low	<0.08 very low	>18 very high	>0.1-0.2 low
NADD	Chikwawa Escarpment	Eutric Cambisols, Haplic phaeozems	50-100	Loamy sand to SCL	5.5-7.0	5-10 low	>0.12 med-very high	6-18 low	>0.2 med-very high
	MidShireValley	Chromic Luvisols Cambisols	100-150	Sandy loam to sand clay	5.5-6.5	5-10 low	<0.08 very low	<6 very low	>0.2 med-very high
	Lower-Shire Mwanza Ftslop	Eutric Fluvisols Cambisols	>150	Loamy sand sandclay lm	5.0-6.5	>10	<0.12	>18	>0.2
	Mwabvi & Lengwe Upland	Eutric Cambisols Haplic Luviso	50-100	Sandy loam	5.5-7.0	>10 med-very high	0.08-0.12 Low	6-18 Low	>0.2 med-very high

Source: MoA (1991)

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[7] MADD is Machinga Agricultural Development Division, and Ngabu ADD

Table 4: Soil physical and chemical characteristics and fertility rating of the study areas (Nkhatabay and Mangochi Districts)

Soil origin	Crop trial	Depth	pH (H_2O	Soil pH rating	Sand %	Silt %	Clay %	Text Class	OM %	N %	Rating of N (Fertility)
Nkhatabay	Maize	0-20	5.0	Moderately acid	43	13	44	SC	0.52	0.03	Very low
		20-40	4.5	Acid	20	10	70	C	0.62	0.03	Very low
	Tobacco	0-20	4.9	Acid	37	7	57	C	0.58	0.03	Very low
		20-40	4.5	Acid	20	10	70	C	0.38	0.02	Very low
	Cassava	0-20	5.4	Moderately acid	7	27	67	C	0.89	0.04	Very low
		20-40	5.7	Slightly acid	7	7	87	C	0.65	0.03	Very low
	Control	0-20	4.6	Acid	33	20	47	C	0.84	0.04	Very low
		20-40	5.0	Moderately acid	17	10	73	C	0.41	0.02	Very low
Mangochi	Maize	0-20	6.1	Almost neutral	53	20	27	SCL	0.96	0.05	Very low
		20-40	6.1	Almost neutral	40	23	37	CL	1.82	0.09	Low
	Tobacco	0-20	5.7	Slightly acid	40	23	37	CL	1.13	0.06	Very low
		20-40	6.0	Almost neutral	30	23	47	C	1.62	0.08	Low
	Tobacco/ maize	0-20	5.5	Slightly acid	40	23	37	CL	0.89	0.04	Very low
		20-40	5.9	Slightly acid	40	13	47	C	1.24	0. 06	Very low
	Control	0-20	5.8	Slightly acid	33	23	43	C	1.72	0.09	Low
		20-40	6.0	Almost neutral	50	20	30	SCL	1.17	0.06	Very low

Survey data (2001). OM=organic matter

2.6 Soil Nutrient Balances

Soil fertility is not static. On the contrary, it changes constantly and its direction (accumulation or depletion) is determined by the interplay between physical, chemical, biological, and anthropogenic processes. This dynamism is also reflected in terminology such as nutrient cycles, budgets, or balances, referring to inputs and outputs in natural ecosystems and managed agro-ecosystems, to which nutrients are added and from which nutrients are removed (IFDC, 1999). As the world population keeps growing, balanced ecosystems are on the decrease and nutrient ledges all over the world have become increasingly imbalanced (Smaling et al, 1997). Malawi faced with one of the fastest population growth rate in SSA on one hand, and constrained by limited suitable arable land for agriculture on the other hand, is not exceptional to this predicament. Calculation of nutrient balances for Malawi is highly desirable. However, such literature for Malawi is not locally available. Hence this study relies mainly on the work done by IFDC (1999). In order to show what is happening to the soil nutrient resource in Malawi, the following sections present the nutrient balances based on the current levels of cropping and soil management, trend of the soil organic matter between the 1970s and 1990s and, maize response to nutrient *inter alia*.

Good soil management is crucial for maintaining and improving soil productivity in Malawi. In order to have a clear picture of what is happening to the physical accounts of the soil resource, calculation of nutrient balances becomes important (Smaling et al, 1997). Estimates of current rate of soil nutrient depletion are important in order to present a case whether indeed nutrient mining is a major contributor to land degradation in Malawi and therefore, a constraint to the sustainable intensification of agriculture production. Estimates of the amounts of nutrient depletion are provided as useful indicators for the design of soil and fertilizer management strategies that can be adopted to prevent land degradation and increase production. Estimates of nutrient depletion are analysed in the context of prevalent circumstances such as current levels of crop production, inherent soil fertility conditions and resilience (or fragility) of the soils, biophysical and agro-ecological environment and population density (IFCD,1999) (see Figure 7).

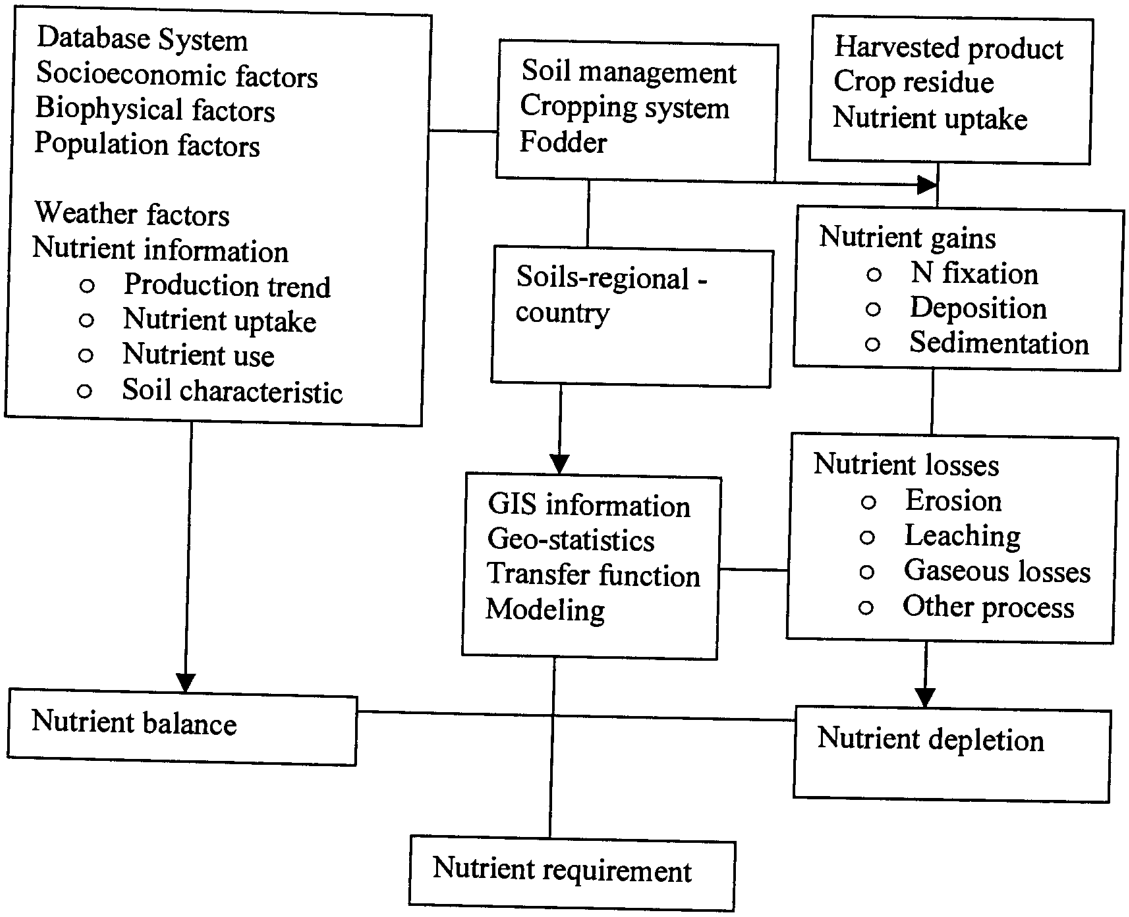

Figure 7: Geo-referenced System to Estimate Nutrient Depletion and Requirements

Source: (IFDC 1999).

Table (5) shows the analysis of crop production and nutrient depletion estimates for the period 1993 to 1995 (IFDC 1999). There is a clear indication from Table (5) that soils in Malawi are losing large amounts of nutrients per year. Soil erosion and nutrient mining are blamed for much of the soil nutrient loss. A number of useful observations can be drawn from the nutrient balance and depletion estimates. Lack of application of required nutrients (NPK) is causing soil nutrient depletion and subsequent reduction of agricultural productivity.

Soil erosion, which is extremely high for Malawi, about 20tons/ha/year, is more likely to degrade soil quality further in the absence of soil conservation policies and if low adoption of soil conservation technologies among smallholder farmers persist. Low application of external inputs means that more nutrients are extracted from the soil than are replaced through external sources, hence soils in Malawi will become more and more unproductive. Since the country's economy is heavily dependent on agriculture, loss of soil productivity has significantly high cost on the well being of the population.

Table 5: Annual Nutrient Balance in Malawi (1993-1995)

	Area ('000ha)	NPK	N	P_2O_5	K_2O	NPK
	2,029	('000mt)	----------------(kg/ha)------------------------			
Annual nutrient requirement		263.8	38.9	37.0	54.1	130.0
Annual nutrient consumption		61.4	18.9	8.4	3.0	30.0
Nutrient balances		-220.8	-47.5	-16.0	-45.3	-108.8

Source: IFDC (1999)

2.6.1 Trend in Soil Organic Matter (SOM) Levels

Build up and maintenance of Soil Organic Matter (SOM) is an important source of fertility particularly when focusing on longer-term interventions. Declining SOM typically results in soils with lower nutrient holding capacities and lower levels of available plant nutrients (Giller et al., 1997). There is much anecdotal evidence that SOM levels in Malawi have declined. Benson (1998) reviewed data sets of Organic Carbon[8] analyses of soil samples collected under two separate programs. The first soil samples were from the Mass Soil Analysis Program carried out by the Soil Fertility Unit at Chitedze Research Station in the 1970s. The second data source was the nation-wide soil sampling exercise carried out in the

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[8] There is direct relationship between the Organic Carbon content of the soil and the Soil Organic Matter (SOM) content--the per cent of SOM is typically calculated as being 1.75 times the per cent Organic Carbon content.

early 1990s by the extension staff in each ADD. Comparable data sets from both programs could only be compiled for Blantyre, Kasungu, and Lilongwe ADDs. Table (6), provides evidence that SOM has been declining. Except for Blantyre, there is significant difference in the mean organic carbon for the two periods. Consequently, soil nutrients stock has been declining. This reinforces the findings according to calculations of nutrient balances indicating that at current cropping levels and management, soil nutrients are being depleted enormously (Table 5). Without additions of nutrients from external sources, it means productivity of the soils is rapidly declining.

Table 6: Trend in Organic Carbon Levels Between 1970 and 1990s

	BLADD		KADD		LADD	
	1970s	1990s	1970s	1990s	1970s	1990s
Mean Organic Carbon (%)	1.38	1.24	2.05	1.75	2.29	1.58
Signifcance of t-test comparing difference of means	0.096		<0.001		<0.001	
Sample % characterised as sandy (S or LS)	11	-	37	24	93	31
Sample % characterised as Loam (SCL or SL)	68	-	56	76	4	68

Source: Benson (1997), adapted from Hardy (1998)

Further evidence of declining soil fertility in Malawi is demonstrated using data from on-farm nutrient trials for the period 1972 and 1996 (Figure 8). Maize was cultivated continuously without any application of nutrient from external sources such as commercial fertilizers. The graph indicates a declining trend of maize yield over time. The yield decline has mainly been associated with deteriorating resource base (declining soil fertility). However, yield levels of smallholder farmers are usually lower than those of research stations. It is argued that effects of declining soil fertility on productivity will also obscure any potential gains from maize breeding (Hardy, 1998). Declining maize yield trend depicted in Figure 8 closely resemble yield trends of most of the smallholder farmers in Malawi for the fact that most of them also continuously cultivate maize crop on the same piece of land without any application of external inputs to replenish the soils.

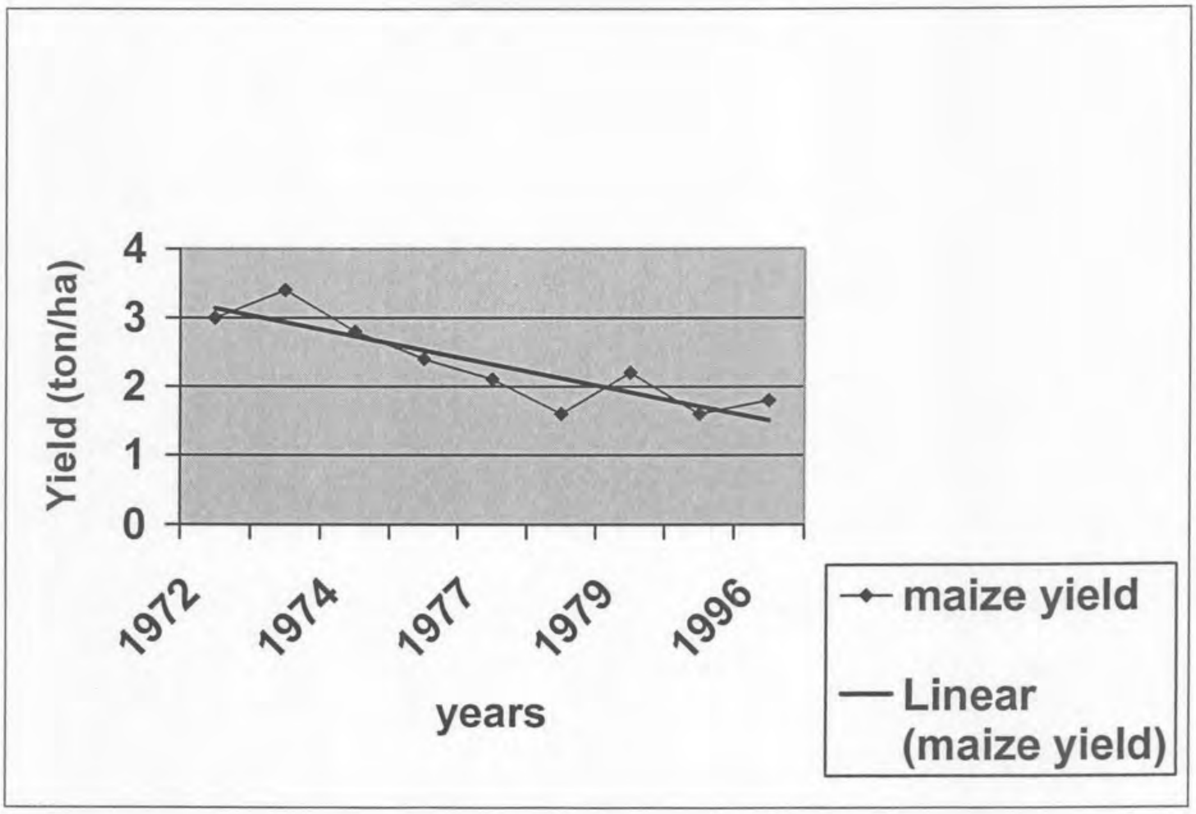

Figure 8: Mean maize yield/ha with no input application: Nutrient response research trials in Malawi.

Source: Data adapted from Benson (1998)

2.7 Concluding summary

Most of the arable farming in Malawi is done on Luvisols (Alfisols; Ferruginous soils), Ferralsols (Oxisols, Ferrallitic soils) and acrisols (Ultisols; Ferrallic soils). Among the soil physical properties, soil structure and effective depth are the most important for agriculture. Most of the soils in Malawi have deep effective depth. Of the upland soils, the Luvisols have good soil structure that is quite stable under proper cultural practices. However, under unimproved agriculture, continuous use of the soil, as is the case under smallholder farming, is bound to destroy the soil structure. Noteworthy, most soils in Malawi are of poor quality as evidenced by low levels of nitrogen and phosphorous, key elements for crop production in Malawi [Tables 3(a-c) and (4)].

Nutrient balances indicate a negative balance, meaning that the current farming system is depleting the soil resource stock. Soil erosion and crop harvesting coupled with unbalanced nutrient application are the major causes of the soil quality depletion. Declining soil organic matter as calculated for the period between 1970 and 1990, confirms that nutrient stock is being depleted. Declining soil productivity as evidenced by continued reduction in maize yield over the years, is consequent to the depleting soil nutrient stock. Therefore, food insecurity among smallholder farmers will continue to worsen until there is a reversal to the current trend of land degradation.

CHAPTER III

MEASURING THE ECONOMIC IMPACTS OF SOIL DEGRADATION: Survey of the Literature

3.1 Introduction

Considering the important role of soil conservation techniques to the curtailment of soil erosion among the smallholder farmers in Malawi, the previous chapter dwelt on the analysis of factors that influence the incidence and extent of adoption amongst this category of farmers. However, the severity of soil degradation in Malawi can be much appreciated at both farm and policy levels if the true economic costs due to this problem are properly analysed. Hence, measuring the economic impacts of soil degradation, in particular soil mining and soil erosion, is the major thrust of this study. This chapter briefly reviews soil fertility and the soil degradation problems in Malawi. Models that predict soil erosion are also discussed. A discussion on linking land degradation and crop productivity is thoroughly presented. Finally, a detailed review of some approaches that have been used to measure the economic impacts of land degradation is also presented.

3.2 Soil Fertility and Soil Degradation

Soil fertility is a function of many physical, chemical and biological properties that, together with climate and other factors, determine the suitability and potential productivity of land for agricultural uses. The essential attributes of natural fertility include soil structure and rooting depth, organic matter and trace nutrient content, plant-available water reserves and soil biology (Lal, et al., 1989). Soil degradation can be described as a process by which one or more of the potential ecological functions of the soil are harmed. These functions relate to biomass production (nutrient, air, water supply and root support for plants) filtering, buffering, storage and transformation (e.g., water, nutrients and pollutants), and to biological habitat and gene reserves. Since total land area is fixed, using the land for agricultural production does not exhaust the physical land area but rather exhaust the quality of topsoil especially when agricultural production is coupled with imbalanced application of external inputs such as commercial fertilizers and manure. Also, erosion depletes land quality factor: depth of the topsoil and hence a loss of all essential nutrients and organic matter that support agricultural production. As a result yield drops or the same output levels are attained at higher costs (through extensive use of external inputs such as fertilizer). Soil degradation is therefore a process that lowers the current and /or future capacity of the soil to produce goods and services. Two categories of soil degradation processes are identified, displacement of soil material (e.g., soil erosion by water or wind forces) and in-situ soil deterioration covering chemical (loss of nutrients, salinization, acidification, pollution) or physical (soil compaction, water logging) soil degradation.

Soil degradation in Malawi is mainly due to water induced soil erosion (loss of topsoil) and loss of nutrients through crop harvest coupled with inadequate and imbalanced fertilizer application. Loss of topsoil results in soil nutrient loss but importantly also, destruction of soil physical structure. Soil degradation can be either the result of natural hazards, or of unsuitable land use and inappropriate land management practices. Unbalanced fertilizer use, deforestation of fragile lands, lack of soil conservation, and overgrazing are some of the human activities causing soil degradation in many parts of the world especially in developing countries. In measuring the economic costs of soil erosion and soil mining, we will confine ourselves to the impact of current smallholder soil and crop management systems on soil quality over time.

3.2.1 Causes of soil degradation

Evidence of exhaustion of arable land under agriculture is found throughout history and in all parts of the world (Brown 1981; Stocking 1984). Most soil degradation is related to effects of farming, though some may be due to long term climatic trends. A number of explanations have been offered as causes of soil degradation, which include population pressure, poverty and sheer ignorance. Whatever the underlying socio-economic cause of soil degradation, from an economic perspective, the effect is the same, that farmers behave as if they value short-term profits obtained from activities which degrade the soil more highly than they value the benefits of soil conservation (Bishop, 1992).

One of the most highly invoked explanations for land degradation in developing countries is high rate of population growth, leading to demographic pressure on land resources. In Malawi, it is reported that high population has put much pressure on the agricultural land resulting in small land sizes per household (World Bank, 1987). However, studies from around the world have failed to establish a direct causal link between population growth and degradation of soil and other renewable resources (Guizlo and Wallace 1994). Nevertheless, evidence from other studies explains why farmers may not choose an economically optimal rate of soil degradation (Bishop, 1992). The widespread prevalence of market, policy and institutional failures means that farmers do not always take into account the full costs of soil degradation to society. Such failures distort economic incentives, leading farmers to deplete soil assets at economically sub-optimal or inefficient rate, which may be too fast or too slow compared to socially optimal rates of soil exploitation. According to Bishop (1992), the underlying causes of inefficient land use are:

- the presence of non-marketed and uncompensated external impacts;
- high rates of time preference that diminish the present value of future yield losses;
- the availability of technical substitutes for natural soil fertility and alternative assets;
- inappropriate policy incentives that advertently discourage soil conservation; and
- technical and economic constraints that prevent farmers from adopting soil conservation practices.

A brief discussion of these factors is given below:

3.2.1.1 External impacts

External impacts or externalities are any costs or benefits that are not reflected in the market prices causing a divergence between private and social costs and benefits of actions of economic agents. For example, a typical negative externality resulting from soil erosion on agricultural land is the sedimentation of downstream reservoirs while protection of watershed provided by trees is a positive externality. Such off-site costs and benefits are not reflected in the prices of agricultural outputs and hence are not taken into account in decision-making. However, these represent real costs and benefits felt by other economic agents downstream.

Such externalities are not only difficult to measure in most cases, but also are rarely documented or understood.

3.2.1.2 Time preference

Time preference refers to the simple fact that most people prefer current income to future income. Pure time preference and marginal opportunity cost of capital are reflected in the discount rate, which is commonly used to compare present and future costs and benefits. Private individuals are often presumed to have high degree of time preference (impatient), thus employ higher discount rates, on average, compared to society as a whole. The reason is that society lives forever and that also, society can diversify investment to effectively minimize risk. This divergence between public and private rates of time preference leads individuals to discount future benefits excessively and thus to consume assets that society as a whole would have rather conserved (Markandya and Pearce, 1988). This leads to higher private than social optimal rates of consumption.

3.2.1.3 Substitutes

Technical innovation is largely devoted to devising substitutes for, or increasing the productivity of scarce factors. The depletion of scarce natural resources poses a threat when it is considered essential to future economic opportunities i.e., if there is no apparent substitute for the resource, if degradation is irreversible and/or if its future value is uncertain but believed to be high (Pearce et al., 1990). Natural resources may seem less essential in the industrialized nations, where fertilizer, irrigation and other technical inputs offer farmers some considerable flexibility, and where alternative economic opportunities are more widely available (Bishop, 1992).

3.2.1.4 Policy incentives

Most countries have instituted a host of policies affecting agriculture, including measures that stimulate production, and others which dampen output. Many of these schemes have significant impacts on land use and soil conservation practices, because of the way they modify relative returns to certain crops and relative costs of inputs or methods of cultivation. Policies may aggravate the problem of excessive soil degradation, or alleviate it. Changes in land use patterns can arise directly and intentionally, through policies affecting the price of farmland or incentives for conservation (e.g., land taxes or subsidies).

3.3 The Relationship Between Soil Properties and Productivity

Although erosion is considered the major agent of soil degradation worldwide [Dudal, 1982; Lal, 1990; Larson et al., 1983], the large-scale effects of erosion on productivity of soils are not yet well known. Quantifying the impact of soil erosion on crop productivity has not been easy because of the complexity of crop response to soil erosion (Pierce and Lal, 1994). The productive capacity of a given soil varies spatially due to variations in soil properties, climate, management, and plant genetics (Daniels and Bubenzer, 1990). Relating soil properties to yield is confounded by the fact that as management input increases or as agriculture becomes technologically advanced, the relative contribution of soil to crop yield diminishes (Pierce and Lal, 1994). Managed inputs can often mask soil erosion damage but to what extent inputs can compensate for soil erosion damage needs further investigation. However, considerable efforts have been directed toward quantifying the relationship between soil properties and crop productivity [Kang and Osimane, 1979; Huddleston 1984; Kayombo and Lal, 1986; Pierce 1990; Aune and Lal, 1995]. In fact, Lal (1984) summarized some of the traditional approaches used to measure the impact of soil erosion on productivity (Table 7). However, relating changes in soil properties induced by soil erosion (real, perceived, or simulated) to crop yield has been a common method for assessing erosion's impact on productivity [Cassel and Fryrear, 1990; Lal 1987; Pierce, 1990; Stocking, 1984]. Pierce (1990) came up with some general conclusions drawn from 50 years of soil erosion and productivity research in the United States (Table 8). Although complex, it is nonetheless important to assess soil erosion's impact on crop productivity in order to plan for agricultural development, to assess the adequacy of food resources for the world's population, and to evaluate agricultural policies at local, regional and national levels (Wolman, 1985). Knowledge of how soil erosion affects productivity is key to developing practices and policies for the restoration of eroded soils.

Table 7: Traditional research approaches used to evaluate erosion's impact on crop productivity.

Method	Description	Comment
Artificial soil removal	manual removal of soil surface to different depths	erosion is selective: does not simulate natural condition
Greenhouse	comparative productivity evaluation under greenhouse conditions for surface vs. subsoil horizons	provides information on fertility but cannot simulate soil structure in field; should be validated under field conditions
Long-term variable management	long-term field trials comparing different soil surface management or cropping systems	difficult to separate management effects from erosion effects
relating soil properties to crop yield	relating erosion-induced alterations in soil properties to crop yields	alterations in soil properties can be caused by intensive cultivation
Topsoil depth/crop yield	relate crop yields to remaining depth of topsoil	natural pedogenic factors can produce differential topsoil thickness in landscape
Reconnaissance survey	relate crop performance and yield to qualitative assessment of past soil erosion (e.g., soil erosion class)	assessments are subjective ;degree of past erosion difficult to quantify
Erosion simulation	rain and wind simulators used to accelerate rate of soil removal	does not address long term soil changes; equipment expensive
Modelling	prediction of erosion's impact on soil properties and productivity	existing models poorly validated in field

Adopted from Pierce and Lal (1994)

Table 8:General conclusions drawn from 50 years of erosion and productivity research in the United States

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- yield levels of many of these studies were low relative to present production levels and study durations were for few years only
- management inputs were sufficient to restore production to levels of undisturbed soils and that the degree to which that was possible was related to the characteristics of sub-soils
- under limited or no fertiliser amendments, yields were often highly related to depth of topsoil
- there is a relationship between crop yield and soil depth
- the ability to find uneroded sites is uncertain and limits assessment of past erosion
- other effects of erosion have been largely ignored
- the effects of erosion on soil productivity are hard to visualise. They are long-term and, at least temporarily, often masked by technology.
- the spatial relationship and variability of soils within the landscape have generally been ignored in soil erosion studies

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Source: Pierce (1990)

In modelling soil erosion and productivity loss, soil properties such as soil organic carbon (SOC), acidity (pH and Al saturation), nitrogen, available phosphorous (P), exchangeable potassium (K), soil bulk density, rooting depth, and weed infestation have been chosen because of their importance in determining productivity of Oxisols, Ultisols, and Alfisols, which are the common soil groups in the tropics (Stewart et al., 1991). One major shortfall of many models linking soil erosion to productivity losses is that they are usually site-specific [Pierce and Lal, 1994; Aune and Lal, 1995]. However, there is no prescription for what comprises an appropriate model (Pierce and Lal, 1995). Stocking (1984) suggested that an appropriate or effective model should have (a) readily available inputs, (b) an output that can link directly to economic or conservation planning decisions, (c) physical/ mathematical expressions to link the steps connecting erosion to yield losses/fertility decline/productivity. A brief explanation of some soil properties that influence productivity is given below.

Nutrient availability

Nutrient availability is an important soil property for productivity and is significantly altered by soil erosion (Pierce and Lal, 1994). Erosion induced changes in the nutrient supplying capacity of soils can be significant. Nitrogen (N) is one of the most important soil nutrients influencing maize production in SSA. However, soil N is a highly labile property and no single soil analysis is adequate to predict its supply to crop over the growing season. For this reason, the effect of N on crop productivity should not be calculated using soil analysis but rather be base on long-term data of crop response to N-fertiliser (Aune and Lal, 1995). Other critical nutrients in the tropics are phosphorous and potassium.

Rooting depth

Rooting depth is an important physical factor in soil productivity because it determines soil reserves of water and nutrients (Aune and Lal, 1995). Other than subsoil acidity, poor soil aeration and presence of hardpans, accelerated soil erosion reduces rooting depth. Admittedly, there is no direct method for measuring the effect of rooting depth on productivity. However, experimental data available from studies designed to evaluate the effects of factors limiting rooting depth are useful in establishing the functional relationship. These experiments include sub-liming, sub-tillage, and soil surface removal studies. Noteworthy, the critical value of rooting depth for maize is 23cm. Mean water holding capacity of soils in the tropics is about 1.3mm /cm soil (Lal, 1987). This implies that soil depth of 23 cm has an available soil water holding capacity of 30 mm (Aune and Lal, 1995).

Bulk density

Bulk density is an important soil physical property because it influences crop productivity in the tropics (Stewart et. al., 1991). It affects water infiltration, root growth and uptake of nutrients and water (Babolola and Lal, 1977).

3.4 Predicting Soil Erosion Impact on Productivity

While there is agreement on the need for predictive capabilities, there is no consensus on which of the varied approaches used to predict soil erosion's impact on productivity is most appropriate (Pierce and Lal, 1995). There are two basic approaches to developing predictions: statistical models and biophysical simulation models. Cassel and Fryrear (1990) cite three classes of statistical models:

- regression models in which crop yields are regressed against one or more variables including soil properties, landscape characteristics, and climate variables;
- multivariate and factor analyses, which use data transformation within multivariate data sets. These often delineate cause and effect relationships not detectable with other statistical techniques and identify soil properties significant in defining crop productivity (Bruce et al., 1989);
- geostatistical models, which analyse the variance structure of spatially distributed data (soil properties and erosion processes) and use the knowledge of spatial variation to predict the areal distribution of properties.

Multiple regression models are the most commonly used, particularly in developing countries, to relate measured soil properties to crop yield for specific environment and cultural conditions (Pierce et al., 1983). The Universal Soil Loss Equation (USLE) and SLEMSA are examples of regression type parametric models that have been used widely to predict long-term erosion impacts on soil productivity [Pierce et al., 1983; Kiniry et al., 1983; Stockings 1986; Arens 1989; Bishop 1992; Brekke et al., 1999]. This section gives a thorough review of both the empirical statistical models and the biophysical simulation models.

3.4.1 Empirical models for predicting impact of soil erosion

Erosion research as known today started in the United States of America (USA) in 1917 and the first model for predicting soil erosion was proposed by Baver in 1933 (Lal, 1990). However, the Universal Soil Loss Equation (USLE) [Wischmeier and Smith, 1978] and Productivity Index (Kiniry et al., 1983) are examples of regression type parametric models that have been used widely to predict long-term erosion impacts on soil productivity [Pierce et al., 1983; 1984]. The USLE is a deterministic (or an empirical) method for estimating average soil loss in tons per hectare as a function of five composite variables: rainfall erosivity index, the inherent susceptibility of the soil to erosion by water, a combined slope length and steepness factor, crop cover and management, and a correction factor for 'supplemental' conservation practices. Although USLE is one of the most extensively used erosion predictive models in the USA and other parts of the world [Lal, 1990; Morgan, 1988; Foster et al., 1982a; Williams, 1981; 1975; Onstad and Foster, 1975], it has some major shortfalls. Among the major shortcomings of the USLE are the following:

- its failure to account for re-deposition;
- the model is designed to predict soil loss from small plots and, therefore, extrapolation to national level attracts a lot of errors and limits the reliability of the results;
- use of USLE in regions with conditions different from those where it was developed (USA) encounters problems limiting its prediction power [Elwell, 1978a,b; Foster et al., 1982b; Wendelaar, 1978; Wischmeier, 1976].

Accordingly, some researchers have disputed the predictive ability of this model under tropical conditions (Stockings, 1987). Some improvements to the USLE have been made to come up with a revised Universal Soil Loss Equation (RUSLE). Integrated changes included seasonal variation in soil erodibility, new methods of calculating cover management factors, new conservation practice values, rainfall runoff erosivity for western rangelands, and computerisation of the algorithms. RUSLE is also capable of accounting for rock fragments in and on the soil. However, an important limitation in both the USLE and RUSLE is that they do not explicitly represent fundamental hydrologic and erosion processes (Renard et al., 1991). Most importantly, in order to use either model outside the USA, it requires that the models be calibrated to local conditions.

Elwell and Stocking (1982) developed an alternative model for Southern Africa. The Soil Loss Equation for Southern Africa (SLEMSA), was designed for use in countries with limited capacity to generate the physical data required by USLE and other models. Unlike USLE, SLEMSA only requires three input parameters: the rainfall energy interception of each crop, the mean soil loss on bare fallow plot of known slopes and a topographic factor for other slopes. Malawi and Zimbabwe share common climatic and soil conditions. As such, the parameters for Zimbabwe would be applicable for Malawi.

A modified version of SLEMSA was developed for reconnaissance level evaluation of erosion hazard (Stockings et. al., 1988). The methodology was designed to make relative assessment of the risk of erosion over large areas, expressed in Erosion Hazard Units (EHU). The latter model uses precipitation data to estimate rainfall energy, which is combined with an index of soil erodability to calculate an erosion index (I_b). The protection provided by vegetal cover is also incorporated, along with average slope.

3.4.2 Simulation models for predicting impact of soil erosion

Erosion prediction is moving away from empirical models like USLE to physically based erosion prediction models in order to describe more accurately the various erosion processes and thereby improve prediction of soil erosion. Simulation models have become important. Since1980s alternative approaches to measure soil erosion impact on crop productivity have involved the use of biophysical simulation models. This approach relies on computerized mathematical models of physical and biological processes linked together in a central system. Some of these models focus heavily on the physical processes of soil erosion and/or sediment movement. Other models focus on the physiological development of a specific crop. The Erosion Productivity-Impact Calculator (EPIC) was the first simulation model developed for the sole purpose of simulating erosion's impacts on crop productivity (Williams et al., 1984). Developed in the mid-1980s, the model has been widely used to assess soil erosion and crop productivity on virtually every continent in the world [Grohs, 1994; Barbier, 1996]. Because soil degradation can take many decades to impact on crop productivity, the EPIC model was originally designed to achieve the following four goals:

- develop a realistic physically based erosion prediction model with readily available inputs;
- include the capability of simulating processes over long time horizons;
- produce valid results over a wide range of soils, crops, and climates;
- provide a model that is computationally efficient.

The physical components of EPIC include weather simulation, surface and subsurface hydrology, erosion process, nutrient cycling, plant growth, tillage and management and soil temperature. The model is characterized as a lumped parameter model because the drainage area considered, usually around one hectare, is assumed to be spatially homogeneous. The model is designed to consider vertical variation in soil properties associated with different soil types and conditions (Lal, 1997).

Another important model that has been used to assess erosion's impact on productivity is the Nitrogen-Tillage-Residue Management (NTRM). NTRM model was developed by Shaffer et al. (1983) to evaluate the effects of soil, climatic and crop factors that limit crop yield through soil erosion. This model is especially useful for identifying management alternatives to alleviate erosion-caused constraints to crop yields. In general, if a crop model effectively describes the important soil-related processes that regulate crop production, then a crop model, along with information about the rates of soil erosion and their effect on soil properties, will allow prediction of erosion's effect on productivity.

Other simulation models include the Productivity Index (PI) developed by Pierce et al. (1983). Pierce et al. (1984) used PI to predict the long-term erosion impacts on soil productivity for soils in the Corn Belt regions of the U.S.A. This model is based on assumption that reduction in potential crop yield by erosion is due to adverse changes in soil profile characteristics to 1-m depth. Soil properties considered include pH, available water capacity, soil bulk density, and soil organic carbon content. However, extensive validation is desired for this model under diverse soil profile characteristics, plant rooting depth, and climatic conditions.

Although biophysical simulation models, such as EPIC, have proved to be valuable research tools for assessing the potential impact of soil erosion and management practices on crop productivity, they are not substitutes for agronomic research. The reliability of the results of simulation models depends on the accuracy and availability of the input data, validity of the assumptions, and application of the model within the boundary conditions in which it was developed (Pierce and Lal, 1994). Most simulation models generally demand substantial data. Most developing countries in SSA, such as Malawi, do not have detailed databases. In addition, some of these models have not been adequately validated using scientifically defensible data (Cassel and Fryear, 1990). According to Pierce (1990), the whole process of quantifying and predicting erosion's impact on crop productivity requires:

- a clear identification of soil properties that regulate crop productivity;
- a coordinated monitoring program that quantifies the rate and extent of erosion induced change in soil quality, erosion damage to crops, and indirect effects on crop productivity discussed earlier;
- a coordinated research program designed to support and/or validate the models; and
- a standardization of field and laboratory methodologies that would allow the establishment of minimum data sets for evaluating erosion effects on soil productivity, regionally or even globally.

3.5 Approaches to Measuring the Economic Costs of Land Degradation

Implicit in the concept of land degradation (soil erosion and soil mining) is the notion that agricultural land use removes some useful nutrients from the land bringing about deterioration in its quality and reducing its productivity. Models for predicting soil land degradation's physical impact on crop yields have been discussed in the previous section. However, physical impacts of land degradation on crop yield entail economic costs. The economic costs of soil erosion are usually separated into two, on-site and off-site costs. On-site refers to the direct effects of soil degradation on the quality of land resource itself, often expressed in terms of reduced agricultural productivity. Off-site costs refer to the indirect effects of soil degradation, which take the form of externalities such as siltation. These downstream damages impose costs on the other members of society not directly involved in causing the erosion.

Most economic analysis of soil erosion has been carried out in the US, where since the 1970s the issue has received much public attention (Ervin and Ervin, 1982). Earlier work on this subject mainly concentrated on conservation and adoption. Dating back to the late 1950s, literature in this area ascribes a key role to institutional factors, information and attitudes (Ciriacy-Wantrup, 1952). Researchers emphasized the need to solicit farmers' perceptions and monitor their decisions (Ervin, 1982). However, since the 1970s, more formal modelling such as linear and dynamic programming techniques as well as optimal control models gained importance and appeal to analysing the economic costs of soil erosion [Brekke et al., 1999; Eaton, 1996; Pagiola, 1993; McConell, 1983; Seitz and Swanson, 1980]. Other approaches included the replacement cost approach and the productivity loss approach. This section reviews the approaches that have been used to measure the economic costs of land degradation.

The approaches that have been used to measure economic costs of land degradation can be separated into two groups: those that are static in nature and those that are dynamic. A static analysis seeks an optimal number or finite set of numbers. Static optimisation models do not trace effects or changes over time. In contrast, dynamic optimisation models generate solutions for a complete optimal time path of each choice variable and not just a single optimal value (one period) (Chiang, 1984). Examples in this category include the optimal control and dynamic programming models.

3.5.1 Static models of valuing impacts of soil degradation

Static models for valuing impacts of soil degradation can be grouped into two: direct valuation methods such as the replacement costs method (RCM) and productivity loss method, and static optimisation models such as linear programming (LP[9]).

3.5.1.1 The replacement cost method (RCM)

The replacement cost approach calculates the loss of major nutrients (e.g., N, P, and K) as a result of any degrading processes such as erosion or crop harvesting and assign a value to it by using the equivalent cost of replenishing the soil fertility through the application of external inputs such as commercial fertilizers. Empirical soil erosion predictive models like USLE and SLEMSA have frequently been used to estimate levels of erosion. Regression analysis is then used to establish a statistical relationship between soil erosion and losses of

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[9] LP models are often extended to handle temporal aspects in multi-period formulations

major soil nutrients such as N, P and K. The value of such losses is then determined through the RCM.

The replacement cost method has been widely used due to its ease. Solorzano et al., (1991) examined effects of soil erosion in Costa Rica and found that annual replacement costs were equal to 5.3-13.3 per cent of annual value-added in agriculture. Stocking (1986) working in Zimbabwe, estimated nutrient loss in terms of nitrogen, phosphorous and organic carbon, and calculated the cost of replenishing these nutrients. A set of data taken from experimental plots during the late 1950s and early 1960s was used. The data represented over 2000 individual storm soil loss events on four soil types and numerous crops, treatments and slopes. Regression analysis was employed to establish a statistical relationship between soil erosion and losses of the three nutrients. Assuming an average rate of sheet erosion for each of the four major farming systems in the country (crop and range-land on communal and large-scale farming land), the amount of nutrients lost per year was calculated. Stockings (1986) then extrapolated the experimental data to the country as a whole for both communal and commercial farming systems engaged in grazing and arable land production. This study assumed that all nitrogen and phosphorous losses were to be replaced by fertilizer every year in order to maintain soil fertility.

However, Norse and Saigal (1992) summarized the pioneering work of Stocking (1986) and concluded that Stocking's study overestimated the costs of soil erosion in Zimbabwe by almost 20 per cent due to its neglect of nutrient input sources. The replacement approach used by Stocking 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 (Bishop, 1992). The replenishment cost approach does not take into account the thresh-hold beyond which the effects of erosion are irreversible and cannot be rectified. Soil erosion affects several yield determining parameters, such as soil depth and nutrient availability [Hailu and Runge-Metzger, 1992]. Thus, when soil erosion has destroyed the soil physical structures like rooting depth, nutrient replenishment approach may under-state effects of soil erosion. Another major weakness of this approach is that it is a cost-based rather than benefit based valuation. This approach is remedial in focus unlike the benefit-based valuation e.g., computing the marginal value of soil quality. The latter approach instils in the user a sense that soil is an asset and has a value. The speed of the asset depreciation will thus depend on the way the asset is used and cared for. Comparably, where one is concerned with sustainable use of soil resource, the benefit-based valuation, which indicates a marginal value of soil quality, is more proactive in approach. For example, if producers are made aware of the marginal value of their land's quality they would protect and put it to the best use possible.

3.5.1.2 The productivity loss method (PLM)

In developing countries, productivity loss approach has been widely used to measure economic losses due to erosion. Practically, the widely used empirical predictive models like USLE and SLEMSA have been used to predict levels of soil erosion. Based on previous research in Nigeria, carried out at the International Institute for Tropical Agriculture (IITA), physical soil loss in tons per hectare per year can be considered a proxy for declining soil fertility (Bishop, 1992). Multiple regression analysis of data from controlled experiments at IITA revealed that soil loss measured in tons per hectare was a reliable predictor of changes in soil nutrient content, soil pH, and moisture retention (Lal, 1981). Aune and Lal (1995) working on erosion research data from Kasama region in Zambia established a functional relationship between erosion and crop productivity loss. Thus, the empirical erosion predictive models are linked to the multiple regression models to establish the functional relationship between erosion and yield productivity losses.

Among the well-known studies that have used the crop productivity loss approach are those by Bishop and Allen (1989) on Mali, Bishop on Malawi (1992), Magrath and Arens (1989) on Java, and Pierce (1984) on Corn Belt in the U.S. Bishop and Allen (1989) estimated cropland erosion in an area comprising about one-third of Mali's most productive cultivated cropland. They then used regression models of erosion-yield loss relationships developed by Lal (1981) at the International Institute for Tropical Agriculture (IITA) in Nigeria. The IITA equations allowed the prediction of the effects of cumulative natural soil loss, in tons per hectare, on yields of degraded soils relative to yields on newly cleared (uneroded) plots (Lal, 1987). To derive crop productivity losses due to soil erosion, net returns "with erosion" were subtracted from net returns "without-erosion". Bishop and Allen's (1989) approach has its own problems. For example, if net returns computed on the plots supposedly to be "with erosion" includes some costs which represent farmers' efforts to counter effects of erosion, then the method understate the true cost of erosion. Also, the requirement to subtract net returns from land "with erosion" from net returns from land "without" erosion is another limiting factor where land is scarce i.e., virgin land may not be available.

Grohs (1994), working on a case study in Zimbabwe, linked estimated soil erosion to crop yields using two empirical models of erosion-yield relation. First, average annual sheet erosion on cropland was estimated for every district using SLEMSA. Yield impacts were then calculated using CERES and EPIC models. The former links erosion, expressed as a reduction in depth of the fertile horizon, to soil water holding capacity and thus to maize yield. Yield losses for maize per centimetre of soil loss were estimated at 0.3-1.4 percent. EPIC links erosion to changes in both soil chemical and physical properties (i.e., nutrient losses as well as depth) and accordingly generates slightly higher estimates of yield loss (0.7-3.3 percent per cm soil loss for maize). Calculated yield losses are combined with farm enterprise budgets and data on average yield and cultivated area to derive estimates of on-site costs of erosion, reported as USD0.7-2.1 million in 1989. Another study is Sutcliffe's (1993) work on Ethiopia who related data on productivity declines to erosion estimates based on the USLE, and combined a soil-life model with a water requirement satisfaction index.

Bishop (1992) used the productivity loss method to measure economic costs of soil erosion in Malawi. This is the only existing study in Malawi that has tried to estimate economic losses due to erosion in the country. This study adapted results from the erosion hazard in Malawi carried out by Khonje and Machira (1987) using SLEMSA. The study converted the Erosion Hazard Units (EHU) into expected soil loss, by simple regression analysis. A database of land use was compiled. A mean rate of soil loss by rural development project (RDPs) and by districts was calculated from gross arable land. For Malawi, a mean rate of soil erosion was estimated to be 20 ton/hectare/year on gross arable land. Using crop budgets, yield losses arising from soil erosion were used. The author made an assumption that farmers reduce the use of variable inputs in the same proportion as gross revenue declines. Applying the estimated percentage yield loss directly to gross crop margins, the study came up with an estimate of economic losses arising from erosion. Gross margins were defined as gross revenue per hectare (mean yield multiplied by the prices offered by the Agricultural Development and Marketing Corporation, ADMARC), less the total cost per hectare of using all recommended inputs (seed, fertilizer, and pestcides) but not including labour inputs. Labour was assumed fixed. However, it is worthwhile to note that input application levels (fertilizers, pesticides) in Malawi are by far below the recommended requirements. Further, the ADMARC prices used in this study were not market determined but rather were fixed (and usually stayed unchanged for long periods) and therefore, would not offer any incentive for farmers to apply recommended inputs. Reduction of gross margins over a period of time should not therefore be specifically linked to the decline in land productivity as the authors assumed because it could also result from the effects of the fixed producer prices (ADMARC prices), hence farmers failed to offset the high cost of production as input prices increased over the years.

3.5.1.3 The hedonic pricing method (HPM)

Hedonic pricing is the indirect approach to valuing soil degradation. It compares the sale of or rental price of plots that differ only in the extent of physical degradation. In principle, the difference in productive capacity will be reflected in prices, which in turn reflect the present value of net returns over time. Hedonic pricing has been used to value effects of soil degradation on agricultural land in North America, with mixed results (Bishop, 1995). Hertzler et al. (1985) evaluated the loss of future productivity due to soil erosion on farmland in Iowa at over USD400 per hectare, but found that this cost was not reflected in land prices. Gardner and Barrows (1985) using data from Wisconsin demonstrated that conservation is only capitalized into land prices when the need for such investment is obvious. The implication of these studies is that soil degradation is not automatically reflected in land prices, even where land markets are relatively well developed, due to lack of information on the extent of erosion and its effect on productivity. Hedonic pricing is generally not applicable where land markets are poorly developed, or when land markets are distorted by speculation or public policy (Bishop, 1995). These constraints are acute in most developing countries such as Malawi.

3.5.1.4 Normative approaches: Static optimisation models

Static optimisation models such as linear programming have also been used in land degradation studies. Barbier (1998) carried out a study on induced innovation and land degradation in Bukina Faso using a linear programming model (LP) of economic behaviour with a biophysical model of plant growth and the condition of the soil. The LP was specified at village level, and had its objective the aggregate welfare of the community, measured as discounted value of future monetary income and opportunity cost of leisure, subject to constraints on the level, quality and distribution of key production factors (livestock numbers, land, capital, soil condition) and on market demand for food. It was assumed that all resource allocation and production decisions were made on the basis of a three year planning horizon. Simplified production functions were used to represent farmers' yield expectations for cotton, sorghum and irrigated rice. In the LP model, yields depended on type and fertility of soil, amount of input application (fertilizer). It was also assumed that insufficient soil depth and insufficient soil organic matter (SOM) depletes yield. Parameters for the production function were obtained from the results of the EPIC model developed by Williams et al., (1987) which was calibrated with real data from different sources (see Barbier, 1996). Barbier (1998) used the Target MOTAD (minimizing of total absolute deviation) method to simulate farmers' aversion toward risk. The model is multiperiodic, but limited by the duration of the assumed planning horizon. Since yield and soil erosion outcomes are affected by stochastic weather events a recursive framework allowed adjustments to be made between expected and actual outcomes each year. The multiperiod model was solved for each year and assumed that farmers held expectations about most likely outcomes for relevant random variables. The model was solved 40 times representing 40 future years. Given the model's solution for the year *t* and its optimal cropping pattern and yields, and associated level of soil erosion, EPIC was then run to simulate random weather outcomes, and to generate 'actual' outcomes for yields and erosion that year. The actual values were then used to adjust total production and income, and to recalibrate the closing stock of cash and grain and the level of soil erosion that entered the constraint set for the multiperiod model in year *t*+1.

In another study, Shiferaw and Holden (1999) applied a whole-farm linear programming model that contained multiple production activities and a number of behavioural constraints to understand the question of soil erosion and smallholders' decisions in the Highlands of Ethiopia. This model assumed the following four major goals: maximisation of net income, self-sufficiency in major staples, generation of cash to meet various needs, and achievement of acceptable levels of leisure. Model constraints included limits on owned and rented land, labour, oxen power, subsistence needs, animal feed requirement, capital/credit for fertiliser, cash income, and restriction on crop rotations. The effect of soil erosion on crop yield (productivity) was estimated from a production function estimated for the major crop (teff) based on time series data collected by the Soil Conservation Research Project (SCRP) in other similar areas in the highlands. Although Shiferaw and Holden's model was able to examine long-term effects on resource use and conservation behaviour of smallholder farmers, the steady-state equilibrium would not give guidance on the optimal control path for the extraction of the soil stock.

.3.5.2 Dynamic optimisation methods

In a dynamic optimisation problem, current output levels do not only affect current returns, but also future output and future net returns. Current extraction level will influence future extraction levels and net benefits. The problem faced by the decision maker in dynamic optimisation is, therefore, to extract given levels of resource at each period of time that will maximize the total net returns over time. The solution of a dynamic optimisation problem would thus take the form of an optimal time path for every choice variable (Chiang, 1992). There are three alternative approaches to dynamic optimisation: calculus of variation, dynamic programming and optimal control. This study presents examples of some studies that have used these approaches, precisely, the dynamic programming and the optimal control using the maximum principle.

3.5.2.1 Dynamic programming

One of the early influential models in dynamic optimisation for economic costs of soil erosion was the one developed by Burt (1981). Burt presented a formal inter-temporal model of soil use for farms in Palouse area of the northwestern U.S.A. He used a dynamic programming formulation with two state variables: depth of topsoil and the percentage of organic matter in the soil; and the percentage of land devoted to wheat as a control variable. However, according to Chiang (1992), dynamic programming models are known to suffer from two shortcomings:

- primary attention is focused on the optimal value of the function (optimal value function) rather than on the properties of the optimal control path as in optimal control theory;
- solution of continuous-time problems of dynamic programming involves the more advanced mathematical topic of partial differential equations which do not often yield analytical solutions.

3.5.2.2. Optimal control methods

Given the limitations of dynamic programming approach, techniques provided by the optimal control method are more powerful for the inter-temporal analysis (Chiang, 1992). One of the early key studies using optimal control is that of McConell (1983), who developed a simple model using optimal control theory in which soil depth and loss were incorporated into a single production function. The focus was on the inter-temporal path of soil use including the conditions under which private and social optima diverge. The paper also gave insight into some effective instruments of erosion control. In the tradition of natural resource economics, McConell(1983) argues that soil is an asset that must compete with other assets. The returns to the farmer are characterized by two elements. First, the value of soil as input to agricultural production in both current and future periods, which thus contribute to profits. Second, the amount and productivity of the soil at the end of the planning period will affect the potential resale value of the farmer's land, reflecting a capital element. One objective of McConnell's model was to explain circumstance under which it is optimal for a profit-maximising farmer to tolerate soil erosion. The first order conditions yield the normal profit maximizing result: farmer should use soil up to the point at which value of its marginal product equals its marginal cost. This value is simply the additional current profit while the cost is the foregone future profit from depleting the soil in the current period plus the capital loss at the end of the planning period. McConnell's model generates results similar to other natural resource management problems and helps us understand the inter-temporal trade-off that farmers make (explicitly or implicitly) in their decisions on soil erosion (Eaton, 1996). The first order conditions show that any change that would increase the costs of soil loss or decrease the benefits would lead to reduction in soil loss, and vice-versa. However, McConnell's paper ignores effect of soil quality on productivity by assuming that soil quality is constant.

Another useful study utilizing the theory of optimal control for economic cost analysis of soil erosion is that of Hertzler et al., (1985), who computed user costs of soil erosion and their effect on agricultural land prices. The study considered whether land markets efficiently capture the degradation in soil quality caused by erosion. Using a dynamically optimal adoption of soil-conserving technologies, crop rotation and pesticide regimes, they calculated differences in land prices observed in a completely inefficient and perfectly efficient markets. Total user cost of erosion measured the present value of decreases in static rents over time because of declining yields and increasing operating costs. The user costs of erosion included the costs of soil, phosphorous and potassium. Dynamic rents were measured as static rents minus total user costs. Productive value of land was calculated as the present value of the stream of static rents that equalled to dynamic rents capitalised at the discount rent. This allowed total user costs, as one component of dynamic rent, to be capitalized separately, showing the effect of erosion on the value of land in a perfectly efficient market. An important finding in this study was that soil erosion significantly reduces the productive value of land per acre by USD170. This value would double if user costs of phosphorous and potassium were added, except that the loss of nutrients does not permanently degrade the soil as can be replenished by application of fertilizers. The study was, nevertheless, not conclusive on whether inefficient land markets influence farmers to over-exploit the soil. The impact of land price is of particular interest to economists examining soil erosion in the U.S. or anywhere else where private property rights and markets for agricultural land are fairly developed. In Malawi, however, property rights and markets for agricultural land are poorly developed and lacking in many aspects. This approach is, therefore, less applicable.

Brekke et al. (1999) used optimal control theory (maximum principle) to calculate soil wealth for Tanzania. In their approach, they combined SLEMSA model and other soil scientific model (The Tropical Soil Productivity Calculator) developed by Aune and Lal (1995) to link crop productivity and soil degradation into an inter-temporal optimisation framework. The approach by Brekke et al. (1999) is unique in that there is a clear distinction between soil-mining and soil erosion problems. In the soil-mining model, land productivity (land quality) is a function of nutrient stocks. Hence land productivity is constrained only by nutrient levels. Erosion model captured the negative effects of soil erosion on crop productivity due to reduction in rooting depth i.e., soil depth within which crop roots are able to utilize nutrients and water. Unlike extraction of nutrients, rooting depth reductions are irreversible. A key assumption in this study was that the government's objective was to maximize soil wealth. Smallholder farmers chose labour, capital investment and level of input (fertilizer) to maximize soil wealth i.e., present value of soil rent.

3.6 Concluding Summary

In spite of the overwhelming recognition that erosion is the major agent of soil degradation worldwide, still, large-scale effects of soil erosion on productivity of soils are not well known. Pierce and Lal (1994) acknowledged that quantifying the impact of soil erosion on crop productivity has not been easy because of the complexity of crop response to erosion. However, considerable effort has been directed towards quantifying the economic costs of soil degradation.

Soil degradation has long-term consequences and static models, which form the bulk of studies that have so far been carried out in Africa to quantify economic costs of soil degradation, do not account for the inter-temporal dimension of optimal resource management. To deal with this shortcoming, an inter-temporal optimisation framework, which considers soil in a time-dependent resource extraction perspective, is regarded as a better approach in quantifying the economic impact of soil degradation.

CHAPTER IV

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

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

4.1 The Analytical Framework and The Optimal Control Approach

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

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

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

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

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

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

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

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

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

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

4.2 Modelling Agricultural Output and Soil Mining

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

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

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

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

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

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

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

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

$$H(Q_t, LS_t, KS_t) = h - M(Q_t, LS_t, KS_t) \tag{4}$$

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

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

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

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

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

4.3 The Optimal Control of Soil Quality Depletion

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

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

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

Subject to:

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

S_0 is given

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

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

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

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

The first order conditions for optimal control (FOC)

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

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

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

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

$$f_{LQ_t} = \frac{\partial f}{\partial LQ_t} \tag{9}$$

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

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

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

4.4 Interpreting FOCs

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

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

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

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

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

a. value of Q produced from an extra unit of soil nutrient stock used, Pf_{S_t}
b. dynamic benefits from more dense canopy (Q) $\lambda_t H_{S_t}$ [15]which in turn contributes to lower soil decay (erosion) through M and hence conserve soil nutrients.

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

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

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

4.5 Input Substitution

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

$$\frac{Pf_{LQ} - w_L}{w_L} = \frac{D_{LQ} - H_{LQ}}{H_{LS}} \tag{11}$$

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

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

$$\frac{w_F}{w_L} = \frac{G_F}{H_{LS}} \tag{12}$$

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

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

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

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

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

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

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

4.6 Socially Optimal Use of Soil Nutrient Stock

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

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

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

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

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

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

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

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

4.7 Comparing Dynamic with Static Optimisation Solutions of Farmers

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

CHAPTER V

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

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

5.1 Specification of the Empirical Soil Mining Model for Malawi

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

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

$$Q = A * LQ^{\alpha_L} S^{\alpha_S} \qquad (20)$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

5.2 Solutions of the Optimal Soil Mining Model

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

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

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

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

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

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

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

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

5.2.1 Steady State (SS) Solutions

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

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

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

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

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

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

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

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

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

5.3 Estimation of the Specified Model Parameters

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

5.3.1 Sources and methods of data collection

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

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

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

5.3.2 Estimation of Cobb Douglas (CD) production function

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

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

where:

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

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

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

ε = Error term

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

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

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

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

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

5.3.2 Measuring parameters of the soil depletion and regeneration functions

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

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

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

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

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

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

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

where:

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

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

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

ε = Error term

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

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

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

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

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

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

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

Table 11: Model parameter estimates

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

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

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

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

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

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

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

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

Table 12: Comparative analyses results

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

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

5.6 Sensitivity Analysis

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

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

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

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

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

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

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

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

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

CHAPTER VI

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

6.1 Introduction

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

6.2 Soil Conservation in Malawi

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

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

6.3 Investing in Soil Conservation

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

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

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

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

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

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

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

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

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

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

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

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

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

6.4. Approach and methods of the study

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

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

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

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

6.5 Specification of the Empirical Model

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

$$\mathrm{Y} = \beta' X + \varepsilon \tag{6.1}$$

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

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

$$z_i = 0, otherwise \tag{6.2b}$$

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

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

$$\Pr ob(z_i = 1) = \Phi(X_i \beta / \sigma) \tag{6.3}$$

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

$z_i = 0$, otherwise

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

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

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

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

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

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

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

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

Simplified as:

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

where

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

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

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

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

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

6.6 Choice of Variables

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

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

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

6.7 Data and Data Limitations

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

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

6.8 Household Characteristics in the Study Areas

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

6.8.1 Household type

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

6.8.2 Literacy level

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

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

6.8.3 Land acquisition and land-holding size

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

Table 14: Land ownership

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

Figures in parentheses are number of households

6.8.4 Farming system, soil erosion and soil conservation practices

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

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

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

Table 15: Period land under cultivation

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

Table 16: Level of soil erosion

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

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

Table 17: Reasons sighted for yield decline in the area

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

6.9 Concluding Summary

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

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

CHAPTER VII

EMPIRICAL RESULTS OF THE SELECTIVE TOBIT ANALYSIS

7.1 Introduction

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

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

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

7.2 Empirical Results and Discussion

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

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

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

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

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

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

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

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

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

*significant at 10% or lower

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

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

* significant at 10% or lower

7.3 Concluding Summary

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

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

CHAPTER VIII

SUMMARY, CONCLUSIONS AND IMPLICATIONS FOR POLICY AND RESEARCH

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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APPENDICES

Appendix 1: Current Hamiltonian version of the optimal control model of the soil mining problem

$$N_C(F, LQ, LS, KS, \lambda) = [P_t f(S_t, LQ_t) - w_F F_t - w_K KS_t - w_L(LQ_t + LS_t)] \\ + m[H(Q_t, LS_t, KS_t) - D(Q) + G(F_t)]$$

where $m = e^{\delta t}\lambda_t$ (1)

The first order conditions (FOCs) for optimal control

$$\frac{\partial N_C}{\partial F_t} = 0 \Rightarrow w_F = m_t G_F \qquad \Rightarrow m_t = \frac{w_F}{G_F} \tag{2}$$

$$\frac{\partial N_C}{\partial LS_t} = 0 \Rightarrow w_L = m_t H_{LS_t} \qquad \Rightarrow m_t = \frac{w_L}{H_{LS}} \tag{3}$$

$$\frac{\partial N_C}{\partial KS_t} = 0 \Rightarrow w_K = m_t H_{KS_t} \qquad \Rightarrow m_t = \frac{w_K}{H_{KS}} \tag{4}$$

$$\frac{\partial N_C}{\partial LQ_t} = 0 \Rightarrow \left(Pf_{LQ_t} - w_L\right) = m_t\left(D_{LQ_t} - H_{LQ_t}\right) \tag{5}$$

where $\left(Pf_{LQ} - w_L\right)$ defines the net price NP_{LQ} giving:

$$m_t = \frac{NP_{LQ}}{D_{LQ} - H_{LQ}} \tag{6}$$

Current co-state equation of motion is given as below

$$\dot{m} = -\frac{\partial N_C}{\partial S} + \delta m = -[Pf_s + m(H_S - D_S)] + \delta m$$

$$\dot{m} = -\frac{\partial N}{\partial S} + \delta m = -Pf_s + m[(D_S - H_S) + \delta] \tag{7}$$

However, at steady state (SS), $\dot{m} = 0$, then equation 7 becomes 7’below

$$Pf_s = m[(D_S - H_S) + \delta] \tag{7’}$$

At steady state, $\dot{S} = 0$ meaning that $S_{t+1} = S_t = S$, entails that equation of motion 3, $\dot{S} = H(Q_t, LS_t, KS_t) - D(Q_t) + G(F_t)$ reduces to

$$G(F) = D(Q_t) - H \tag{8}$$

In other words, level of replenishment required to maintain soil nutrient stock should offset the net depletion of soil nutrients measured as the net effect of depletion/ decay and regeneration $(D - H)$.

Combining 2 and 7’ to eliminate m

$$Pf_s = \frac{w_F}{G_F}[(D_S - H_S) + \delta]$$

$$\frac{Pf_s G_F}{w_F} = \delta + (D_S - H_S) \tag{2b}$$

Combining equation 3 and 7’ to eliminate m

$$Pf_s = \frac{w_L}{H_{LS}}[(D_S - H_S) + \delta]$$

$$\frac{Pf_s H_{LS}}{w_L} = \delta + (D_S - H_S) \tag{3b}$$

Combining 4 and 7' to eliminate m

$$Pf_s = \frac{w_K}{H_{KS}}[(D_S - H_S) + \delta]$$

$$\frac{Pf_s H_{KS}}{w_K} = \delta + (D_S - H_S) \qquad (4b)$$

Combining 5 and 7' to eliminate m

$$Pf_s = \frac{NP_{LQ}}{D_{LQ} - H_{LQ}}[\delta + (D_S - H_S)]$$

$$\frac{Pf_S (D_{LQ} - H_{LQ})}{NP_{LQ}} = \delta + (D_S - H_S) \qquad (5b)$$

if $G_F = g = 1$, then from equation 2 $w_F = m$ and equation 7' becomes

$$Pf_s = w_F[(D_S - H_S) + \delta] \qquad (6b)$$

Note that in chapter IV, 2b to 5b correspond to equations 16-19

Appendix 2:Specification of the soil-mining model and calculating reduced form solutions of the choice variables $(LQ, F, KS, LS, S \,\&\, \lambda)$ at the Steady State (SS).

The following functions have been specified in equations 20-26 of chapter V:

A. The CD production function

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

B. The relationship between erosion E and Q (canopy) has been specified as:

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

C. Contribution of soil conservation to the decay process is specified in this study as CD function of soil conservation efforts through the use of labour (LS) and capital (KS):

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

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

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

The aggregate natural regeneration and decay process function H becomes:

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

D. The depletion (or damage) function $D(Q)$ is specified as a linear function of Q:

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

E. The nitrogen augmenting function $G(F)$ is specified as a linear function of fertiliser F:

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

After substituting 20-26 in the objective function, the Hamiltonian can be rewritten as:

$$N(LQ,F,KS,LS,\lambda)=e^{-\delta t}\{(P(A*LQ^{\alpha_L}S^{\alpha_S})-w_K K-w_F F-w_L(LQ+LS)\}+\lambda[H-D+G]$$

where H, D and G as specified above (24, 25 and 26).

FOCs for above decision problem :

$$\frac{\partial N}{\partial F}=e^{-\delta t}(w_F)=\lambda_t\frac{\partial G}{\partial F}=\lambda g \tag{27}$$

$$\frac{\partial N}{\partial LQ}=e^{-\delta t}(\alpha_L P*A*LQ^{\alpha_L-1}S^{\alpha_S}-w_L)=\lambda_t\left[\frac{\partial H}{\partial LQ}-\frac{\partial D}{\partial LQ}\right] \tag{28}$$

$$\frac{\partial H}{\partial LQ}=H_{LQ};\ \frac{\partial D}{\partial LQ}=D_{LQ}$$

$$\frac{\partial N}{\partial LS}=e^{-\delta t}w_L=\lambda_t\frac{\partial H}{LS};\qquad \frac{\partial H}{\partial LS}=H_{LS} \tag{29}$$

$$\frac{\partial N}{\partial KS}=e^{-\delta t}w_K=\lambda_t\frac{\partial H}{\partial KS};\qquad \frac{\partial H}{\partial KS}=H_{KS} \tag{30}$$

$$\dot{\lambda}=-\frac{\partial N}{\partial S_t}=-(e^{-\delta t}P*A*LQ^{\alpha_L}S^{\alpha_S-1})+\lambda_t\left[\frac{\partial H}{\partial S}-\frac{\partial D}{\partial S}\right] \tag{31}$$

$$\frac{\partial H}{\partial S}=H_S;\qquad \frac{\partial D}{\partial S}=D_S$$

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

Using the above system of FOC equations of the soil mining model (equations 27-32) one can derive reduced form solutions for the choice variables, KS^*, LS^*, LQ^* F^*, S^* and λ^*.

A3.1 Steady State (SS) Solutions

Assuming a SS equilibrium path $\left(\dot{S}=\dot{\lambda}=0\right)$ the FOC can be written as derived in chapter IV (equations 16-19):

$$\frac{Pf_s G_F}{w_F} = \delta + \left(D_S - H_S\right) \qquad (16)$$

$$\frac{Pf_s H_{LS}}{w_L} = \delta + \left(D_S - H_S\right) \qquad (17)$$

$$\frac{Pf_s H_{KS}}{w_K} = \delta + \left(D_S - H_S\right) \qquad (18)$$

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

Using specification of H given in equation 24 above one can derive:

$$\frac{\partial H}{\partial LQ} = -b\beta\alpha_L \frac{Q}{LQ}\phi e^{-bQ}$$

let $b\phi e^{-bQ} = \zeta$ (3.1)

$$\frac{\partial H}{\partial LQ} = H_{LQ} = -\alpha_L \frac{Q}{LQ}\beta\zeta \qquad (3.2)$$

$$\frac{\partial H}{\partial S} = -b\beta\phi\alpha_S \frac{Q}{S}e^{-bQ}$$

$$\frac{\partial H}{\partial S} = H_S = -\alpha_S \frac{Q}{S}\beta\zeta \qquad (3.3)$$

$$\frac{\partial H}{\partial LS} = \beta_1 LQ^{\beta_1 - 1} KS^{\beta_2}$$

let $LS^{\beta_1} KS^{\beta_2} = C$

$$\frac{\partial H}{\partial LS} = H_{LS} = \beta_1 LS^{\beta_1 - 1} KS^{\beta_2} = \beta_1 \frac{C}{LS} \qquad (3.4)$$

$$\frac{\partial H}{\partial KS} = \beta_2 LS^{\beta_1} KS^{\beta_2 - 1}$$

$$\frac{\partial H}{\partial KS} = H_{KS} = \beta_2 LS^{\beta_1} KS^{\beta_2 - 1} = \beta_2 \frac{C}{KS} \qquad (3.5)$$

From equation 25

$$\frac{\partial D}{\partial LQ} = D_{LQ} = nLQ^{\alpha_L - 1} S^{\alpha_S} = \alpha_L n \frac{Q}{LQ} \qquad (3.6)$$

$$\frac{\partial D}{\partial S} = D_S = nLQ^{\alpha_L} S^{\alpha_S - 1} = \alpha_S n \frac{Q}{S} \qquad (3.7)$$

And from equation 26:

$$\frac{\partial G}{\partial F} = g \qquad (3.8)$$

According to the above $H_S - D_S$, is obtained from equations 3.3 and 3.7

$$H_S - D_S = -\alpha_S \frac{Q}{S} \beta\zeta - n\alpha_S \frac{Q}{S} = -\alpha_S \frac{Q}{S}(n + \beta\zeta) \qquad (3.9)$$

Similarly $H_{LQ} - D_{LQ}$, is obtained from equations 3.2 and 3.6

$$H_{LQ} - D_{LQ} = -\alpha_L \frac{Q}{LQ} \beta\zeta - n\alpha_L \frac{Q}{LQ} = -\alpha_L \frac{Q}{LQ}(n + \beta\zeta) \qquad (3.10)$$

Using the above information, equations 16-19 are accordingly specified as below:

Substituting for $f_s = \alpha_S \frac{Q}{S}$; $D_S - H_S$; and G_F in equation 16

$$\alpha_S P \frac{Q}{S} g = w_F \left[\delta + \alpha_S \frac{Q}{S}(n + \beta\zeta) \right] \qquad (16b)$$

Substituting for f_S; H_{LS}; and $D_S - H_S$ in equation 17 to get

$$\alpha_S \beta_1 P \frac{Q}{S} \frac{C}{LS} = w_L \left[\delta + \alpha_S \frac{Q}{S}(n + \beta\zeta) \right] \qquad (17b)$$

Substituting for f_S; H_{KS}; and $D_S - H_S$; in 18 to get

$$\alpha_S \beta_2 P \frac{Q}{S}\frac{C}{KS} = w_K\left[\delta + \alpha_S \frac{Q}{S}(n+\beta\zeta)\right] \tag{18b}$$

Substituting for $f_S\,; D_{LQ} - H_{LQ}$ and $NP_{LQ} = \alpha_L P\frac{Q}{LQ} - w_L$ in equation 19 we get

$$\alpha_S\alpha_L P\frac{Q}{S}\frac{Q}{LQ}(n+\beta\zeta) = \left(\alpha_L P\frac{Q}{LQ} - w_L\right)\left[\delta+\alpha_S\frac{Q}{S}(n+\beta\zeta)\right] \tag{19b}$$

Using specified SS optimality conditions (equations 16b-19b) plus equation 32, the reduced form solutions for choice variables LQ^{*}, S^{*}, KS^{*}, LS^{*} and F^{*} can be derived.

Using equations 16b &19b we derive 20b below

$$g\left(\alpha_L P\frac{Q}{LQ} - w_L\right) = w_F\left[\alpha_L\frac{Q}{LQ}(n+\beta\zeta)\right]$$

$$g w_L = g\alpha_L P\frac{Q}{LQ} - w_F\left[\alpha_L\frac{Q}{LQ}(n+\beta\zeta)\right]$$

$$w_L g = \alpha_L\frac{Q}{LQ}\left[Pg - w_F(n+\beta\zeta)\right]$$

$$w_L g = \alpha_L A LQ^{\alpha_L-1} S^{\alpha_S}\left[Pg - w_F(n+\beta\zeta)\right]$$

$$LQ^{\alpha_L-1} = \frac{w_L g}{\alpha_L A S^{\alpha_S}\left[Pg - w_F(n+\beta\zeta)\right]}$$

$$LQ = \left[\frac{w_L g}{\alpha_L A S^{\alpha_S}\left[Pg - w_F(n+\beta\zeta)\right]}\right]^{\frac{1}{\alpha_L-1}} \qquad (20b)^{24}$$

Substitute 20b into 16b to solve for S

---

[24] Please note that $\zeta = b\phi^{-bQ}$, and Q is determined (see Brekke et al., 1999)

$$\alpha_S PALQ^{\alpha_L} S^{\alpha_S-1} g = w_F\delta + w_F\left[\alpha_S LQ^{\alpha_L} S^{\alpha_S-1}(n+\beta\zeta)\right]$$

$$\alpha_S PgAS^{\alpha_S-1}\left[\frac{gw_L}{A\alpha_L S^{\alpha_S}\left[Pg-w_F(n+\beta\zeta)\right]}\right]^{\frac{\alpha_L}{\alpha_L-1}} = w_F\delta+\alpha_S w_F S^{\alpha_S-1}(n+\beta\zeta)\left[\frac{gw_L}{A\alpha_L S^{\alpha_S}\left[Pg-w_F(n+\beta\zeta)\right]}\right]^{\frac{\alpha_L}{\alpha_L-1}}$$

Divide through by $AS^{\alpha_S-1}\left[\frac{gw_L}{A\alpha_L S^{\alpha_S}\left[Pg-w_F(n+\beta\zeta)\right]}\right]^{\frac{\alpha_L}{\alpha_L-1}}$

$$\alpha_S Pg = \frac{w_F\delta}{AS^{\alpha_S-1}}\left[\frac{gw_L}{A\alpha_L S^{\alpha_S}\left[Pg-w_F(n+\beta\zeta)\right]}\right]^{\frac{-\alpha_L}{\alpha_L-1}} + \alpha_S w_F(n+\beta\zeta)$$

$$\alpha_S\left[Pg-w_F(n+\beta\zeta)\right] = \frac{w_F\delta}{AS^{\alpha_S-1}}\left[\frac{gw_L}{A\alpha_L S^{\alpha_S}\left[Pg-w_F(n+\beta\zeta)\right]}\right]^{\frac{-\alpha_L}{\alpha_L-1}}$$

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

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

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

let $1-\alpha_S-\alpha_L=\gamma$

$$S^{*} = A^{\frac{1}{\gamma}}\left(\frac{\alpha_L}{gw_L}\right)^{\frac{\alpha_L}{\gamma}}\left[\frac{w_F\delta}{\alpha_S}\right]^{\frac{\alpha_L-1}{\gamma}}\left[Pg-w_F(n+\beta\zeta)\right]^{\frac{1}{\gamma}} \qquad (21.a)$$

Substitute 21a into 20b to solve for LQ

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

$$LQ^{*}=A^{\frac{1}{\gamma}}\left(\frac{gw_L}{\alpha_L}\right)^{\frac{1-\alpha_S-\alpha_L+\alpha_S\alpha_L}{\gamma(\alpha_L-1)}}\left(\frac{\delta w_F}{\alpha_S}\right)^{\frac{-\alpha_S}{\gamma}}\left[Pg-w_F(n+\beta\zeta)\right]^{\frac{1}{\gamma}} \qquad (22.a)$$

From equations (17b&18b) we derive

$$\alpha_S\beta_1 P\frac{Q}{S}\frac{C}{LS}\frac{1}{w_L}=\alpha_S\beta_2 P\frac{Q}{S}\frac{C}{KS}\frac{1}{w_K} \qquad (3a)$$

Eliminating common terms $\left(\alpha_S, P, \frac{Q}{S}, \&C\right)$ (we get an expression for LS

$$LS=\frac{w_K}{w_L}\frac{\beta_1}{\beta_2}KS \qquad (3b)$$

Using equations 16b and 17b we derive:

$$\frac{g}{\beta_1\frac{C}{LS}}=\frac{g}{\beta_1 LS^{\beta_1-1}KS^{\beta_2}}=\frac{w_F}{w_L} \qquad (4a)$$

$$LS^{\beta_1 - 1} = \frac{gw_L}{\beta_1 w_F KS^{\beta_2}}$$

$$LS = \left[\frac{gw_L}{\beta_1 w_F KS^{\beta_2}}\right]^{\frac{1}{\beta_1 - 1}}; \qquad (4b)$$

Equating 4b and 3b, we can solve for KS

$$LS = \left[\frac{gw_L}{\beta_1 w_F KS^{\beta_2}}\right]^{\frac{1}{\beta_1 - 1}} = \frac{w_K}{w_L}\frac{\beta_1}{\beta_2} KS$$

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

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

let $1 - \beta_1 - \beta_2 = \varphi$

$$KS^* = \left(\frac{\beta_1}{w_L}\right)^{\frac{\beta_1}{\varphi}} \left(\frac{w_K}{\beta_2}\right)^{\frac{\beta_1 - 1}{\varphi}} \left(\frac{w_F}{g}\right)^{\frac{1}{\varphi}} \qquad (23.a)$$

Substitute (23.a) into 3b to solve for LS^*

$$LS = \frac{w_K}{w_L}\frac{\beta_1}{\beta_2}\left[\left(\frac{\beta_1}{w_L}\right)^{\frac{\beta_1}{1-\beta_1-\beta_2}} \left(\frac{w_K}{\beta_2}\right)^{\frac{\beta_1 - 1}{1-\beta_1-\beta_2}} \left(\frac{w_F}{g}\right)^{\frac{1}{1-\beta_1-\beta_2}}\right]$$

$$LS^* = \left(\frac{\beta_1}{w_L}\right)^{\frac{1-\beta_2}{1-\beta_1-\beta_2}} \left(\frac{w_K}{\beta_2}\right)^{\frac{-\beta_2}{1-\beta_1-\beta_2}} \left(\frac{w_F}{g}\right)^{\frac{1}{1-\beta_1-\beta_2}} = \left(\frac{\beta_1}{w_L}\right)^{\frac{1-\beta_2}{\varphi}} \left(\frac{w_K}{\beta_2}\right)^{\frac{-\beta_2}{\varphi}} \left(\frac{w_F}{g}\right)^{\frac{1}{\varphi}} \qquad (24.a)$$

At steady state (SS) optimal level of F can be solved from state equation of motion 3 as below:

$$\dot{S} = H - D + G \tag{5a}$$

$$\text{at SS, } \dot{S} = 0 \Rightarrow G = D - H \tag{5a.1}$$

Note that H is specified in equation (24) as $h - \beta\left(\phi e^{-bQ} - LS^{\beta_1}KS^{\beta_2}\right)$ while D is specified in equation (25) as nQ. From 25, F can be calculated at SS as below:

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

$$F = \left[nQ - h - \left(\beta\phi e^{-bQ} - LS^{\beta_1}KS^{\beta_2}\right)\right] / g \tag{25a}$$

Substituting for Q, and C (LS and KS) from equations (21.a to 24.a), we get:

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

(25b)

Appendix 3: Dynamic costs of soil degradation and determinants of adoption of soil conservation technologies by smallholder farmers in Malawi.

Socio-economic questionnaire

Note: This questionnaire must be administered to the household head or any person in charge of field activities

ADD	
DISTRICT	
RDP	
EPA	
SECTION (T.A)	
VILLAGE	
DATE OF INTERVIEW	
NAME OF RESPONDENT	
NAME OF ENUMERATOR	
H/H ID	
CHECKED BY	

1.HOUSEHOLD CHARACTERISTICS

1.1 Table 1: Head of household, marital status, number of members and education level of head

Household head		Marital status of h/h head		Number of Household members	#	Education level of h/h head	
Male	01	Single	01	<15 years		None	01
Female	02	Married	02	15-64 years		Std 1-4	02
Child	03	Polygamist	03	>64 years		Std 5-8	03
		Widowed	04			Form 1-2	04
		Divorced	05			Form 3-4	05
		Separated	06			Tertiary	06

m

2.0 Land size, crops grown, land ownership and acquisition and period involved in soil/land conservation practices

Code 1	**Land size**	**Land ownership**		**Land acquisition**		**Period land under cultivation**		**Land conservation methods used by h/h**		**Years involved in soil conservation**	**Code 2 Level of soil degradation**	**Code 3 If doesn't conserve why not?**
01		Male/husb	01	Purchased	01	< 5 years	01	**Physical**				
02		Female	02	Maternal	02	5<11 yrs	02	Contours	01			
03		Vge headman	03	Paternal	03	11<20 yrs	03	Marker ridges	02			
04		Parents	04	Vge headman	04	>20 years	04	Box ridges	03			
05		Scheme	05	Scheme	05			Terracing	04			
06		Borrowed	06	Estate	06			**Biological**				
07		Estate	07	Others	07			Vertiver grass	05			
		Others	08					Hedgerow intercrop	06			
								Manure	07			

Code1
01 total land area
02 land under cultivation
03 own land
04 rented in
05 rented out
06 borrowed
07 land under fallow

Code 2
01 mild
02 moderate
03 severe

code 3
01 land is still productive though soil erosion is taking place
02 land is too small to accommodate soil erosion structures
03 land is too small and erosion mitigation costs cannot be offset
04 land already highly degraded/eroded and erosion control measures is waste of time
05 tried erosion measures before but gains were not significant
06 household doesn't have enough labor
07 doesn't any benefits of soil conservation practices
08 doesn't know any soil conservation methods

2.2 Crops, cost of land preparation and conservation, inputs and levels of yield

Code1 Crop	Code 2 Cropping system	Area (ha/ acre)	Land preparation (MK)	Weeding (MK)	Cost of Soil conservation (MK)	Soil fertility (input) Code 3	Amount (kg), ngolo	MK	If doesn't apply inputs, why not? Code 4	Part of crop eaten or sold before harvest (kg)	Harvest/yield (Kg)	Amount sold (kg)	MK	Gifts/ ceremonies (Kg)

Code1
01 maize
02 cassava
03 common beans
04 pigeon peas
05 rice
06 sorghum
07 groundnuts
08 tobacco
09 cotton

Code 2
01 sole/mono cropping
02 intercropping
03 crop rotation (ulimi wakasinthasintha)
04 rely cropping (ulimi wamwela)

Code 3
01 fertilizer(specify type)
02 farm yard manure
03 compost manure
04 crop residues
05 agroforestry/tree litter
06 livestock manure

Code4
01lack income to buy fertilizer
02untimely availability of fertilizer
03 unavailability /insufficient of litter or manure
04 too dry for residues to decompose
05 benefits from investment not appreciated
06 don't want to introduce land to chemical fertilizers
07 not aware of benefits
08 lack credit facility

Note: other codes may be added in an area where need be

2.5.2 If it doesn't, why not

01 yields levels have not been affected
02 extension messages have not emphasized on this problem
03 community fails to link declining yields with erosion
04 numerous problems affecting yield levels in the area over shadow effects of erosion on yield
05 erosion is not a serious problem in the area

2.6 Considering the way you use your land, would you say you have any consideration for the future generation?

01 yes
02 no

2.6.1 If yes, what do you do to preserve the quality of land for the future generation

01 practice soil conservation measures (specify)
02 apply inputs (fertilizer, manure etc) to replenish soil nutrients and maintain good quality of land
03 avoid cultivation of marginal areas
04 practice fallow system
06 others (specify)

2.6.2 If no, why not

01 we are barely surviving now and therefore can't concentrate on the future
02 land provided for our forefathers and has provided for us, so will provide for the future generation by itself
03 it is difficult to investment in soil quality when such investment can't pay off immediately (we are not beneficiaries of the investment)
04 it is the government responsibility to preserve the land/ feed its people
05 never had concern for the future generation
06others(specify)

4.0 Assets and bank accounts of the household

(focus should be on assets and bank accounts presently held by the household)

Code 1 productive assets	No.Units	Year acquired	Value bought (MK)	**Code 2** personal assets	No.Units	Year acquired	Value bought (MK)	Accounts held by household	
								Bank	Amount (MK)
								NBM	
								CBM	
								NBS	
								Post Office	
								SACCO	

Code 1
01 hoe
02 plough
03 ox-cart
04 phanga knife
05 water can
06 sprayer
07 sickle
08 wheelbarrow
09 axe
10 modern khola

Code 2
01 radio/recorder
02 bicycle
03 motorcycle
04 wall-clock
05 vehicle
06 modern house (brick wall and iron sheets)

5.0 Main sources of income and expenditure for the household (calculate per annum)

INCOME SOURCES								EXPENDITURE		
Agricultural crops (code 1)	**MK**	**Agricultural related code 2**		**MK**	**Other sources**		**MK**	**Main Expenditure**		**MK**
		Agric. wage labourer	01		Fishing	01		Food	01	
		Dairy/ beef Livestock	02		Formal employment	02		Health	02	
		Poultry	03		Pension	03		Transport	03	
		Land rents	04		Remittances	04		Housing	04	
		Ganyu	05		Carpentry	05		Land rents	05	
		Equipment hire	06		Tailoring	06		Equipment hire	06	
					IGAs	07		Remittances (gives out)	07	
					Gifts	08		Gifts (gives out)	08	
					Aid (govt, NGOs	09		Business	09	

Code1

01 maize
02 cassava
03 common beans
04 pigeon peas
05 rice
06 sorghum
07 groundnuts
08 tobacco
09 cotton

6.0 Access to credit/loan/grants facilities

Code 1	Type of loan Code 2	Source Code 3	Amount received (kg) or MK	Is amount enough?	Repayment mode Code 4	Repayment period code		If doesn't access, why not?		Credit required		Ability to pay back loan	
						.<6mo	01	No collateral	01	Inputs	01	Income from sales	01
						6mo-1yr	02	No credit institutions	02	Cash	02	Govt to assist me	02
						1-5yrs	03	Segregated because of sex	03	Food	03	Group to assist me	03
						>5yrs	04	Not aware of such facility	04	Livestock	04	Needs grant	04
								No need	05			Needs soft loan	05
								Prefer grants	06				

Code 1
01 yes
02 no

Code 2
01 seed input
02 fertilizer
03 cash
04 food
05 livestock

Code 3
01 MRFC
02 farmers' world
03 farmers' finance company
04 NGOs
05 government
06 donor aid

Code 4
01 cash with interest
02 cash without interest
03 food
04 labor
05 same item/ eg seed
06others(specify)

7. Food security and coping strategies

7.1 Do you produce enough food for your household (to be consumed throughout the year)?

01 yes
02 no

7.2 If no, how do the household supplement to cover-up the deficit?

01 purchase with own cash
02 gifts from relatives/friends
03 food for work
04 aid (govt, NGOs)
05 others (specify)

7.3 Does your family sometimes substitute some usual meals/food for less preferred food (e.g., porridge for nsima; madeya for ufa woyera etc)

01. Yes
02. No

7.3.1 if yes, how often?

01. Rarely
02. Often

7.4 What time of the year do you experience food shortage?

01 Soon after harvest (around May-June)
02 Around July
03 Around September
04 Around December
05 Around February

7.5 Does your family reduce number of meals served or reduce quantity of food per individual (in some months) as food insecurity coping mechanism?

1. Yes
2. No

7.5.1 If you sometimes reduce quantity of food and/or frequency of meals which members of the family are often affected?

01 children
02 adult women
03 adult men
04 all family members

7.5.2 In which months of the year is this practice most common?

01 Jan – Mar
02 Apr-Jun
03 Jul-Septr
04 Oct- Dec

7.5.2 Do you ever make nsima from green maize?

01. Never
02. Sometimes
03.(Almost every year)

7.3 At times, are some of your family members involved in activities below as food insecurity coping mechanism

(a) ganyu
(b) Seek temporary work off-farm?
(c) borrow grains
(d) borrow money
(e) receive food aid
(f) sell farm equipment or animals
(g) sell household assets
(h) rent or sell land

7.4 If some members seek ganyu what is the preferred payment?

01 cash
02 food
03others(specify)

7.5 Do you experience or nurse sicknesses frequently?

01 once or twice a month
02 after every two months
03 after every four months
04 after every six months
05 once a year
06 Others (specify)

7.6 Which members of the family are most vulnerable?

01 husband
02 wife
03 children
04 others (specify)

7.7 Do you experience labour shortage in the garden due to the sicknesses?

01 yes
02 no

7.8 If yes, how do you manage field activities?

01 hire private labour
02 reduce land size (area) cultivated
03 skip other field activities (specify)
04 others (specify)

Participatory Rural Appraisal (PRA) Checklist

Note: ***This checklist will be used as a discussion guide during the focus group discussions***

The focus group members should include, but not be limited to, the following:

1. Key informants in the area including staff members of organizations working in the area e.g. extension staff both for agriculture and other organizations i.e., NGOs etc
2. Farmers - need to balance the male and female farmers
3. Youths groups - both in and out of school youths

Note that each Focus group should not exceed 20 people. In cases where more than 20 people are available, it may be appropriate to have two or more focus groups.

A. Main purpose of the PRA

1 To allow smallholder farmers define in their own words and perspective the main factors that have led to the decline in land productivity;

2 To understand from smallholder farmers if they easily connect declining soil fertility and food insecurity from own experience.

3 To understand from smallholder farmers if they easily relate cultivation practices/land management and the problem of soil fertility decline. If they do, how have they changed over time, farming systems and land preservation practices in response to the threat of declining soil fertility in their area.

4 To have an influenced opinion of the smallholder farmers if the evolvement of farming systems, land preservation practices over time reflect more on the communities' concern or rather consideration for the well-being of the future generation.

5 To find out from farmers what can be done by the communities, Government and other Non Governmental Organisation to address the problem of declining soil fertility in the area and the livelihood insecurity in the short and long term.

B. The main discussion topics

B.1 Agriculture

- Food crops
- Cash crops
- Cropping patterns
- Market outlets (input and output)
- Input and output prices and how they influence farmers' decision
- Training needs for extension, food diversification

B.2 Soil Erosion and Declining Soil Fertility

- Soil erosion problem in the area (extent or erosion and damage—declining yield levels)
- Soil conservation practices/programs (specify physical and biological)
- Input use and problems (specify biological and inorganic)
- Access to input
- Knowledge of soil erosion effects and soil conservation methods (extension)

B.3 Food security

- Food production (harvest)
- Adequacy of food from own production
- Food purchases
- Food deficit months
- Coping mechanisms/ survival strategies
- Other sources of income
- Food distribution within the household (traditional/cultural practises) Impact of food insecurity on productivity