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**Economic Analysis of Soil Capital, Land Use and
Agricultural Production in Kenya**

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GÖTEBORG UNIVERSITY

To Helena

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Department of Economics dissertations

ECONOMIC ANALYSIS OF SOIL CAPITAL, LAND USE AND AGRICULTURAL PRODUCTION IN KENYA

Abstract

The *purpose* of this thesis is to investigate economic and natural science aspects of soil management and agricultural production in a developing country context. It does so by theoretical as well as empirical investigation, based on data from field surveys in Kenya's central highlands over several years. The *rationale* for the thesis is the need to increase our understanding of the economics of soil capital, land use and agricultural production in order to design policies promoting sustainable development. The thesis includes papers on: optimal soil use with downstream externalities (Ch. 2); determinants of soil capital and agricultural production (Ch. 3; 4); links between farmers' resource levels, soil properties and agricultural productivity (Ch. 5); and land use-change and determinants of rural-urban migration in Kenya (Ch. 6).

Chapter 2 shows that farmers may need incentives (taxes, subsidies or charges) to induce them to reduce soil erosion and thereby downstream damages. Furthermore we find other factors (low discount rate, tenure security, access to credits, crop insurance) that promote accumulation of soil capital and reduce soil loss and nutrient leakage.

Regression analyses in Chapter 3 show that farmers' soil capital is not a given or fixed factor but depends on soil conservation investments, and the allocation of labour, crops, manure and fertilizer in agricultural production. The wide distribution of soil properties across farms indicates the need to tailor technical extension advice to farmers' preferences and the farm-specific economic and agro-ecological circumstances, and enhance the use of integrated soil analysis, field assessment and detailed soil mapping at farm level.

Regressions in Chapter 4 show that agricultural output is determined not only by farmers' input of land, labour, manure and fertilizer, but also by the quality of soil conservation investments and farm-specific soil properties. Hence, integrating economics and soil science is highly worthwhile in this research area. Omitting soil capital measures can cause omitted variables bias since farmers' choice of inputs depend both on the quality and status of the soil capital and on other economic conditions (e.g. availability and cost of labour, fertilizers and other inputs).

Chapter 5 shows that: relatively richer farmers have higher crop yields; poorer farmers have lower soil nutrient levels; farms with gentle slope and high resource level have the highest land management rating. These results indicate that actions aimed at promoting higher yields and sustainable agriculture will have to differ depending on farmers' endowment, and that agricultural policy advice needs to be adapted to farmers' resource levels.

Chapter 6 shows that farmers have changed their farming system considerably during the last 40 years: introduced new (cash) crops, increased tree cover, reduced terracing, diversified crops and income sources, and increased market orientation and temporary work in cities. The study emphasizes the need to improve extension advice, rural roads, supply of inputs, local ownership of public soil conservation investment programs, access to credits and output markets, and job opportunities for farmers during agricultural off-season e.g. work in local food processing industries.

Preface

A long journey has come to an end. Or at least to a temporary stop in my life. Since I have spent more than enough time on completing this thesis, I think this Preface is the right place to reflect a little on the work I have done, look back, indulge in some introspection and thank all the people, who in various ways have contributed to the completion of this book. For those of you who are more interested in the research as such may skip this section. Others are more than welcome to read on!

Choosing a research subject like mine might seem a little odd and farfetched given my background as an urbanite from the Northern hemisphere. Nevertheless, research is best driven out of curiosity and my interest in development issues goes back as far as I can remember. The real eye-opener was probably when I worked for the Red Cross in Ethiopia in 1988-89. There land degradation is a real binding constraint to rural development. Soil erosion eats into farmers' slopes and pockets. The vicious circle of poverty, natural hazards, unsustainable land use and food insecurity was almost physically tangible. Upon return to Sweden, the offer to join the creation of the Environmental Economics Unit and specialize in environmental economics seemed like a perfect opportunity to combine my interest in economics, environment and development. Moreover, the practical collaboration with, and financial support from Sida offered perfect soil conditions for cultivating these interests. So, given that this thesis originated almost 20 years back, how can it be summarized? Well, in short, by memories and people. These are the two principal ingredients.

Working on this thesis has given me countless memories and experiences. Some of the most memorable ones include the vagaries of hill-side driving on slippery mud roads in Kenya's central highlands, the power of tropical rains on erodible soils, the hospitality and joy among the farmers in the field study area despite deep-rooted poverty and nature's hardships. Some physical memories include the near-death experiences of working with early versions of SAS, vomiting and headache on the trail towards Mt. Kenya (didn't reach the top...), backache of carrying hundreds of soil samples at high altitudes after nights of too little sleep on too short beds on too thin mattresses, the pains of malaria under a single light bulb, the sweetness of Muranga's lady finger bananas, and the odd combination of tastes from washing down ugaali, chapati and sukuma wiki with a luke-warm Coke under the heat of the sun in zenith (i.e. a typical lunch in the field). Or the encounters with farmers in despair after having experienced a year with too little rain, or a year with too much rain – stark reminders to an economist that there is never such a thing as “a normal year” for a small-scale farmer in the tropics.

This thesis would have been nothing without the support from others. Some people have been particularly important. First and foremost, working with Thomas Sterner, my supervisor, friend and colleague, has been a pleasure throughout. “Working” in this case means working in many odd places, under peculiar circumstances and over a long period of time! Innumerable lunches with espresso, walk-away cheese, Kalle's and Hungarian sourbread have provided the main frame within which research ideas and draft papers have been discussed. But our working relationship – and this thesis - has also developed during joint traveling to such diverse places as Mafia Island in the Indian Ocean, the maize fields in Kenya's Central Highlands, south-eastern Ethiopia, tropical agricultural fields in Costa Rica, the Cape in South Africa, at environmental economics conferences in Kyoto, Umeå, Lisbon, Dublin, Southampton, Thessaloniki and Venice. There were also occasions when we definitely did not spend much thought on the thesis, for instance when we stood on shaky legs in stupid goggles in a rattan basket under the hot-air balloon sailing by the winds above Göteborg, or during open sea-kayaking and water polo at Marstrand, or when we had some ale at a pub outside the Westminster Public School, or during knee-breaking dancing in Adams Morgan,

Washington DC, or when we tried Masaai archery inside Hotel d’Afrique... Besides being my supervisor he is also a dear friend. Thomas has always put a lot of trust in my work and me as a person. As one sign of this trust, in the U.S. he bought a car (a beautiful lemon) from me after 2 minutes of technical inspection; another more telling sign of personal trust would be all the interest and dedication he has showed in this long-term project. While charging me with responsibility for undertaking other interesting work tasks, he has always, with patience and enthusiasm, inspired me to pursue and finalize this thesis. Thank You!

Gunnar Köhlin, my dear friend and colleague, deserves many thanks because he was the one who lured me into environmental economics and encouraged me to do a Minor Field Study on the economics of soil conservation in Kenya back in 1991; in many ways the starting point of this thesis! Throughout, he has been a renewable resource of inspiration. In my view he sets a good example by embodying the nowadays rather unusual wish to use the academic tools to improve the world, and assist people in realizing their aspirations. Gunnar the Humanitarian and Gunnar the Facilitator, crammed into the same body, have always been there to help, listen, suggest, push, pull and assist on academic as well as other matters.

Very special thanks go to professor Gardner Brown. In the midst of optimal controls, comparative statics, Hessians and Maximum Principles we have become very good friends. Knowing the theory and being full of economic intuition, he has been a tough discussant sending funny but crushing replies like: “Anders, what you state is true if God created the World based on Cobb-Douglas, but I am sure He didn’t!” or on the economics of soil loss “Yes this expression is correct if Earth is flat, but it isn’t”. Memorable one-liners which made me understand (and never forget!) that there were some weaknesses in the paper, making me think harder, do my homework, sweat, revise and re-submit. But Gardner has always been there to receive and read new drafts with an open mind. Thanks Gardner for all fun and frank comments, full of insights and wisdom, and our fruitful collaboration over the years!

Besides Thomas, Gardner and Gunnar I have benefited from specific advice and comments on the papers in the thesis by several people. In particular I would like to thank E. Somanathan, Peter Berck, Lennart Flood, Daniela Andrén, Martin Linde-Rahr, Menale Kassie, Jesper Stage, Martin Dufwenberg, Mintewab Bezabih, Gete Zeleke, Charles Gachene, Martine Visser, Carolyn Fischer, Peter Parks, Knut Sydsaeter, Francisco Alpizar, Mahmud Yesuf and Adrian Müller.

Mats Segnestam has been a long-time supporter of environmental economics as a viable tool to enhance Swedish development cooperation, and a constant energizer to my efforts to work as an advisor to Sida. Despite Swedish agency bureaucracy and the constant flux of info on environmental degradation in developing countries, Mats has always focused on the opportunities, never given in to despair and always been a source of inspiration to push on in the integration of environmental aspects in Swedish aid. Thank you Mats for all cooperation and support over the years!

In Kenya, I have had the opportunity to meet and collaborate with a large number of interesting and knowledgeable people: Prof. Charles K.K. Gachene at Department of Soil Science, University of Nairobi, who patiently coordinated the soil sample analysis and responded to a host of questions regarding soil science, and on how to interpret the data. Thanks! Prof. Donald B. Thomas at the Department of Agricultural Engineering, University of Nairobi for general advice and the encouragement to focus on quality assessment of soil conservation technologies, and for letting me use your evaluation criteria; Drs. M. Mbegera and F.W. Mbote, former Heads of the Soil and Water Conservation Branch, and J.K. Kiara at Kenya’s Ministry of Agriculture, Livestock Development and Marketing for your interest in the economics of SWC and for your support of my work; Prof. Jan Hultin, who worked for Sida as advisor at Kenya’s Min. of Agriculture at the time of my field studies, showed great interest in my work and even made the effort and joined me to the field – thanks for

interesting discussions on “why farmers do what they do”! Dr. Michael Ståhl and Erik Skoglund, former Heads of Sida’s Regional Soil Conservation Unit in Nairobi, who opened up the Unit for me; your openness gave me unlimited opportunities to access your expertise, and other resource persons like Göran Bergman, Inge Gerremo, Frank Place at ICRAF, Martin Grunder, Anders Eriksson, Åke Lennartsson and Bo Tengnäs, as well as full access to reports and other literature on agriculture and land use in the RSCU/RELMA library.

A good deal of my field work in Kenya and the initial analysis back home was done in collaboration with Mira Ovuka and Per Knutsson. Mira (“miss Milla”) and I spent totally several months together in the field. Given all the challenges and at times very stressful and exhausting situations, it is a wonder how smoothly everything worked out. Representing three different research disciplines, our collaboration gave me many new insights, and besides the special friendship this collaboration created, I thank you Mira and Per for your efforts to make our joint research work!

During the field studies I was also fortunate to have excellent counterparts and support from Muranga’s District Agricultural Office, including the DAO Mr. Nyaga, the Soil Conservation officers and the Technical Extension Agents: David Karau, Francis Muthami, Charles Iruku, Evan Waithaka, Julius Gitau, Stephen Mwangi, and Charles Irungu and all ambitious enumerators. Your local knowledge, practical experiences and strong will to support my work, and to improve the life of the farmers in the area despite little resources, have been constant reminders of the importance of the objectives of this thesis. During the field work I also benefited from discussions with Dr. Anna Tengberg, who worked at Kenya Agricultural Research Institute’s field station in Embu during parts of my field studies. Thanks for interesting discussions, then and afterwards! Last but not least, I owe all the farmers in the field study area innumerable thanks for setting aside precious time to respond to my questions over several years. It has been truly memorable to walk in to your lush shambas and enjoy your delicious bananas, papayas and mangoes right from the trees, and share your pride over crops which have succeeded, disappointment over crops or conservation structures which failed, and your grief over animals and family members who died. Despite poverty, stresses and hardship you were always there to respond to my odd questions. Thank you very much.

*Ever since I came to the Department of Economics, and took part in the creation of the Environmental Economics Unit, I have felt at home. This is of course partly due to my interest in environmental economics, but more importantly due to the fun and professional atmosphere created by all the people working there, now as well as in the past. You have been a source of joy, laughter and many good memories, for instance our excursions to learn about marine life in the waters outside Kristineberg’s Marine lab (reminding me of the fishing scenes in *The Cuckoo’s Nest*), acid rain monitoring in conifer forests outside Göteborg, or ice-skating in Frölundaborg with dare-devils from Zimbabwe, Costa Rica and Zambia, or skiing in Skatås with slipping-and-sliding academics from all corners of the World. Always with a smile, You have made my day!*

Within EEU I have developed friendships and professional relationships with many individuals, who in various ways have contributed to making my work at the Department and on this thesis a pleasure. In addition to those already mentioned, particular thanks go to Fredrik Carlsson, Håkan Eggert, Elizabeth Földi, Olof Johansson-Stenman, Karin Jonson, Karin Bäckteman, Gerd Georgsson, Magnus Hennlock, Åsa Löfgren, Peter Martinsson, Katarina Renström, Jesper Stage, and Anna-Karin Ågren.

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Over the years many people have made my life at the Department particularly joyful and giving. In addition to those already mentioned I would like to thank, in particular, old teachers and colleagues who have all contributed in various ways to develop my interest in economics: Arne Bigsten, Lennart Flood, Hans Bjurek, Lennart Hjalmarsson, Katarina Katz, Johan Lönnroth, Bo Sandelin, Dick Durevall, Daniela Andrén, Per-Åke Andersson, Ola Olsson, Renato Aguilar, Evert Köstner, Lars-Göran Larsson and Wlodek Bursztyn.

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Over the years a diaspora of friends and former colleagues have emerged. Despite the geographical distance you have always been there to discuss research, politics, sports trivia or development issues. Mostly, these individuals are old-timers from the department or other individuals. Persons I would like to mention in particular include Magnus Alveesson, Anders Isaksson, Mattias Erlandsson, Mohammed Belhaj, Wilfred Nyangena, Mahmud Yesuf, Alemu Mekonnen, Tekie Alemu, Moses Ikiara, Wisdom Akpalu, Francisco Alpizar, Razack Lokina, Adolf Mkenda, Lisa Segnestam, Ola Larsson, Jörgen Näslund, Nicholas and Susanna Waters (thanks for early work on the "two-catchment approach" using SIMCA), Per Fredriksson, Jorge Rogat, and Lena Höglund-Isaksson.

Writing this thesis has not followed a linear process. Rather it has been an intellectual project, which has followed me during my professional development. Part of this was the work I did as environmental economist at the World Bank's Africa Department during two years. These years were truly inspiring, a reality check on the relevance of environmental economics in practical applications and brought with it a host of encouraging encounters and professional relationships. Individuals I would like to thank in particular are Jan Bojö, who was my closest colleague and made all conceivable efforts to introduce me to the Bank's work and key staff, Francois Falloux, Hans Binswanger, Jean-Roger Mercier, John Dixon, Kirk Hamilton, and Martin Ravallion. In addition, I owe Jeff Eisenberg at USDA Soil Conservation Service at the time and Elinor Merberg very special thanks for making my stay in Washington most memorable. Thank you!

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Coming back to where I started, my parents Christina and Kalle, have played different but complementary roles in shaping me into the person I am. Besides giving me the necessary tools to take on the challenges of life, crucial moments have been the times when they have encouraged me to explore the World, as opposed to other parents who might have asked about the usefulness of going to China, Romania, New Caledonia or Ethiopia at a young age when one can stay home and earn some decent money. Without your support, I would have done something else and been someone else, which – I am sure – would not have been equally

fun! Thanks also to my brothers and sister and all in the extended family who have been part of the shaping process and contributed to make me appreciate life!

Part of this is of course my wife Helena, who has been with me throughout the whole thesis-writing process, and even assisted in the field work during one year! In many critical respects, she deserves very special thanks. Despite periods of absence during my data collection and other work-related traveling, Helena has always encouraged me in my work in pursuing this thesis. I can understand that she hasn't shared my interest in all the details of econometrics and household micro-economics. That is a good sign of mental health. She has always coped in the best possible ways when I for different reasons have been mentally or physically absent. Thanks, I love You and our three children Elin, Ville and Sixten.

Anders Ekbohm

Brännö, October 30, 2007

Introduction and Summary of the Thesis

A majority of people in a country like Kenya are farmers. In spite of tropical soils that potentially are very fertile they struggle with extreme poverty. The quest for land has pushed the agricultural frontier into areas that were formerly untouched. Forests have been cleared and farmers now use even very steep slopes for their cultivation. Soil erosion is a problem that has caught the attention of policy makers since colonial times. Soil erosion appears to epitomize lack of sustainability; it reduces on-site crop yields, depreciates the land value and creates considerable ecological and economic problems downstream. Sustaining the soil capital thus seems essential for any farmer. Yet it seems that many farmers hesitate or even resist efforts at soil conservation.

From the government's perspective, depletion of soil capital in an agro-based economy with low investments of the resource rent will undermine long-term development. This is particularly relevant in Kenya, where agriculture contributes with >50% of GDP¹, employs 80% of the total labour force, generates 60% of foreign exchange earnings, make up about 45% of government earnings and provide the vast majority of industrial raw materials (Government of Kenya, 2007). At the same time, land degradation is widespread. As an indication, the costs of soil erosion² in Kenya amount to 3.8% of GDP which equals Kenya's total annual electricity production or agricultural exports (Cohen *et al.*, 2006). In view of these facts, there is a need to better understand the incentives for the different players involved in order to promote sustainable agriculture at the household level as well as nationally.

The purpose of this thesis is to investigate economic and natural science aspects of soil management and agricultural production in a developing country context. It does

¹ Including processing produced by agro-based industries.

² Soil erosion is the physical detachment and (downward) transport of soil particles. It degrades soils' physical, chemical and biological properties, reduces nutrient concentrations and impedes plant growth. It is a sub-set of land (or soil) degradation, which is a broader concept including also e.g. salinization, crusting, sealing, compaction and acidification (see e.g. Thomas, 1994; Gachene and Kimaru, 2003).

so by theoretical as well as empirical investigation. The empirical studies use information collected in field surveys in Kenya's central highlands over several years.

The rationale behind writing this thesis is the need to increase the integration between economics and the natural sciences in general, and increase the understanding of the economics of agriculture and soil degradation in particular, in order to design and implement policies facilitating sustainable agricultural development. Researchers in soil science or agronomy have a tendency to do detailed studies on individual issues such as crop choice, fertilizer, pesticides and so forth. Naturally they have a wealth of technical detail but they most often work on controlled plots and they generally ignore economic aspects of human behavior such as incentives and the role of markets. They do not necessarily think of soil as a form of capital and agriculture as production where a farmer is the entrepreneur who optimizes his utility under risk and uncertainty. The economists on the other hand focus on these aspects and are often oblivious to the natural conditions and the multi-dimensional complexities of soil capital, fertilizers and other biological, physical or chemical factors determining agricultural productivity.

Certainly there are exceptions to these generalizations, but in general the integration of economic and natural science perspectives in the study of agricultural production and land use is relatively poor (Barrett, 1991, 1997; Dasgupta, 1995, Dasgupta and Mäler, 1997). This research therefore strives to take a small step in the necessary integration of ecology, soil science and other disciplines into economic analyses in this area.

The thesis includes chapters on: optimal soil use with downstream externalities (Chapter 2); determinants of soil capital (Chapter 3); the role of soil properties and soil conservation investments in agricultural production (Chapter 4); links between farmers' resource levels, soil properties and agricultural productivity (Chapter 5); land use-change, social and ethnic aspects of soil conservation and determinants of rural-urban migration in Kenya (Chapter 6).

Paper 1: Optimal Soil Use with Downstream Externalities

The ultimate purpose of this paper is to understand why agricultural production causes downstream externalities due to soil loss and fertilizer run-off and thereby to be able to suggest remedial policies. The rationale behind the paper is the fact that soil loss and run-off from fertilizer cause serious flow externalities in downstream environments through-out the world and in particular in Kenya. Social costs include loss of health, life and production due to pollution and eutrophication of freshwater resources, reduced life of hydro-power plants, increased turbidity, and degradation of coral reefs and marine resources³. To illustrate, 22% of the world's coral reefs are at high or medium threat from inland pollution and soil erosion; the global costs of reservoir sedimentation amounts to 13 billion US\$ per year (due to 45 km³ lost water storage capacity annually); the mean annual off-site damage costs of flow externalities⁴ in the United States amounts to 4.6 % of the country's agricultural output value.⁵

The analysis is based on an optimal control model in which soil is treated as capital that has to be managed optimally over time. There is already a substantial literature on dynamic optimization of soil capital in economics but the literature does generally not focus on what we see as the prime variable. They generally omit downstream externalities and assume that the individual farmer and society share the same objective function.⁶ In the presence of externalities, there is a discrepancy. In this paper the social planner aims at maximizing the profits from agriculture subject to a soil dynamics-constraint *and external damage costs* caused by downstream contamination from soil loss and fertilizer leakage. These effects are not considered by the farmer who only maximizes profits. It is this comparison that allows us to identify the area in which policies must be implemented.

³ See Clark *et al.*, 1985; Anderson, 1995; Matson *et al.*, 1997; Bryant *et al.*, 1998; Ayoub, 1999; Fabricius, 2004. van Katwijk *et al.*, 1993; Otieno and Maingi, 1993; McClanahan and Obura, 1997; Saenyi and Chemelil, 2003 look particularly at Kenya. References on damages can be found in Moore and MacCarl, 1987; Holmes, 1988; Smith, 1992; White *et al.*, 1997; Shumway, 1990; Horner *et al.*, 1997; Naidu *et al.*, 1998; Bartram and Chorus, 1999; Ballot *et al.*, 2004.

⁴ External costs pertaining to freshwater and marine recreation, water storage, navigation, flooding, irrigation, commercial fishing, municipal water treatment, and municipal and industrial use.

⁵ Bryant *et al.*, 1998; Palmieri *et al.*, 2001; Smith, 1992.

⁶ See e.g. McConnell, 1983; Barbier, 1990; Barrett, 1991; LaFrance, 1992; Goetz, 1997; Grepperud, 1996; 1997a,b 2000; Smith *et al.* 2000; Yesuf, 2004.

Comparative statics analysis shows that factors which promote a low discount rate (tenure security, access to credits, crop insurance etc.) will reduce soil erosion and nutrient leakage, and promote accumulation of soil capital. Socially optimal subsidies for soil conservation will provide an incentive for farmer to build-up soil capital and increase on-site crop production, and reduce nutrient leakage and soil loss. A charge on chemical fertilizers would reduce their use and thus reduce water pollution due to nutrient leakage. However, such a pollution tax will have serious negative impacts on income distribution and food production.

Based on our model results, combined with a discussion on policy instruments, this paper concludes that the government should try to provide incentives which sustain soil capital *and* prevent contamination of downstream environments, where the resource users have few opportunities to negotiate with the upstream farmers, who may even be unaware of the problems they cause.

Paper 2: Determinants of Soil Capital

This paper combines knowledge from soil science and economics to estimate the determinants of soil capital. The mathematical rigour of dynamic optimization forced us in the previous chapter to adopt the somewhat unfortunate convention of measuring soil uni-dimensionally. Yet we know that soil is very complex and multi-dimensional. Since it is the major capital asset for most poor farmers it is very important to understand this complexity better. The rationale for this paper is: 1) the assumption that identification of determinants of soil capital facilitates a better understanding of constraints and opportunities for increased agricultural production and reduced land degradation, and 2) the limited number of studies on this topic in the research literature, particularly empirical applications in a developing country context (Barrett, 1991, Dasgupta and Mäler, 1997). In standard economic models soil is presented as a homogeneous production factor represented by a single proxy such as land area, soil depth or some quality indicator. The important complexities explained by soil science are largely ignored.

The study discusses the soil quality literature (e.g. Karlen et al., 1997, 2002, 2003; Carter 2002) and builds on a model by Jenny (1994), who suggests that soil is formed also by other factors than those established by natural scientists (e.g. climate, biota, topography, parent material). Arguably, soil capital status is also determined by economic factors and farm management choices. Farmers often say they strive to improve their soil and this study allows us to look at the effects of farmers' conservation efforts, production inputs, crop allocation decisions and household characteristics on a number of different soil properties. The study is based on original field survey data collected over four years among small-holders in Muranga District in Kenya's central Highlands, located at 1500 m above sea level (0°43' S, 37°07' E) with a mean precipitation of 1560 mm per year. The data set that combines information on soil capital, proxied by a set of chemical and physical properties⁷, and economic data on household characteristics, labour supply, physical inputs, crop allocation and conservation investments. The study yields both methodological and policy-relevant results.

Regarding methodology, the analysis shows that (i) soil capital is heterogeneous with soil properties widely distributed across the farms, and (ii) farmers' investment decisions and soil management vary widely across farms. Hence simplifications of soil capital, which are common in the economics literature, may have limited validity. On the other hand, soil science research limited to soils' biological, physical and chemical characteristics fail to recognize that soil is capital owned and managed by farmers. They thus run the risk of omitting important socio-economic determinants of soil capital, and excluding the possibility to explain some of the dynamics that are determined by its stock character.

Regarding policy implications, the study shows that farmers' soil conservation investments, allocation of labour, crop choice, manure and fertilizer input indeed determine variation in farmers' soil capital. Particularly strong positive effects on key soil nutrients (nitrogen, phosphorus, potassium) are observed for certain conservation technologies. Extension advice shows unexpectedly no statistically significant effects

⁷ Rates of nitrogen (N), phosphorus (P), potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), organic carbon (C), pH, cation exchange capacity and soil texture (i.e. grain size distribution of sand, silt and clay).

on soil capital. The data show wide distribution of soil properties and farming strategies (e.g. regarding choice of inputs, crops and conservation investments) across the farms. This finding reinforces the need to (i) tailor technical extension advice to the specific circumstances in each farm, and (ii) enhance the use of integrated soil analysis (combining farmer consultations with laboratory soil testing), field assessment and detailed soil mapping at the farm level.

Paper 3: Soil Properties and Soil Conservation Investments in Agricultural Production - a Case study of Kenya's Central Highlands

This paper looks at the importance of specific soil properties and other variables for agricultural productivity. It integrates traditional economic variables, soil properties and variables on soil conservation investments in order to estimate agricultural output among small-scale farmers in Kenya's central highlands. The study has methodological, empirical as well as policy results and builds on similar models⁸, which estimate agricultural production but do not include soil capital and soil conservation technologies in any detailed manner in the production function.

One key methodological result is that integrating traditional economics and soil science is highly worthwhile in this area of research. Omitting measures of soil capital can cause omitted variables bias since farmers' choice of inputs depend both on the quality and status of the soil capital and on other economic conditions such as availability and cost of labour, fertilizers and other inputs.

Empirically the study shows that: (i) models which include soil capital and soil conservation investments yield lower output elasticity of farm-yard manure; (ii) mean output elasticities of key soil nutrients like nitrogen (N) and potassium (K) are positive and relatively large; (iii) counter to our expectations, the mean output elasticity of phosphorus (P) is negative; (iv) soil conservation technologies like green manure and terraces are positively associated with output and yield large output elasticities.

⁸ See e.g. Deolalikar and Vijverberg, 1987; Widawsky *et al.*, 1998; Carrasco-Tauber and Moffitt, 1992; Mundlak *et al.*, 1997; Fulginiti and Perrin, 1998, Gerdin, 2002, and Sherlund *et al.*, 2002.

The central policy conclusion is that while fertilizers are generally beneficial, optimal application is difficult and more is not necessarily better. The limited supply of fertilizers in the local market, combined with the *different signs* of the output effects of N, P and K, respectively, point at the importance of being much more *selective and specific* in the advice provided to farmers on their soil management. Ideally, farmers ought to increase their access to individualized site-specific soil assessment prior to decisions on soil nutrient replenishment, inputs, crop choice and crop management. Further, given the policy debate on the impact and usefulness of government subsidies to soil conservation, our results suggest that soil conservation investments contribute to increase farmers' output. Consequently, government support to appropriate soil conservation investments arrests soil erosion as well as assists farmers' efforts to increase food production and food security.

Paper 4: Farmers' Resource Levels, Soil Properties and Productivity in Kenya's Central Highlands (co-authored with Mira Ovuka)

The purpose of this paper is to examine the correlation between the farmers' resource endowments and their soil productivity, erosion status and land management for different levels of field slopes and precipitation. Although some studies have been conducted in this area of research⁹, the rationale for this study is the general need to enhance the understanding of the links between farmers' resource endowments and farm management. The empirical study is conducted among smallholders in Kenya's Central Highlands, which is subject to severe erosion (Lewis, 1985; Ovuka, 2000).

In order to operationalize the paper's objective, several methods of data collection were used: soil samples were collected from 100 maize fields. Soil nutrient status was identified by analyzing a set of soil properties. During three years, annual maize yields were recorded from the sampled farms; rainfall data was obtained from local gauging stations. Erosion and land management were noted using the Productive Land Use Systems-classification scheme (PLUS, 1994). Farmers' resource levels, proxied by capital and annual income, were recorded in a household questionnaire survey.

⁹ See e.g. Loiske, 1995; Altshul, *et al.*, 1996; Briggs, *et al.*, 1998; Tengberg, *et al.*, 1997, 1998.

The statistical analyses show that there are significant differences in organic C, available P, grain size distribution, maize yield, erosion and land management between farms of different resource level categories. Specifically, the highest maize yields were found among farms with the highest resource levels. The relatively poorest farmers have lower nutrient levels on their fields. Mean values of the soil properties indicate that the rates of both available P and organic C are higher on the gentle slopes compared with moderate (steeper) slopes. The highest rating of land management was found on farms with gentle slope and high resource level (i.e. those relatively more endowed), whereas the lowest rating was found for farms on steeper slopes with low (poorer) resource level.

The results corroborate findings by e.g. Loiske (1995) and Tengberg *et al.* (1998) that farmers' endowment affects their farming strategies. Arguably, the results suggest that different land use and farming systems explain the differences in both soil nutrient status and crop output. The results indicate that actions aimed at promoting higher yields and sustainable agriculture will have to differ depending on farmers' endowment, and that agricultural policy advice needs to be adapted to farmers' resource levels. The study emphasizes the need to sustain farmers' soil fertility (i.e. soil's productive capacity) in order to increase agricultural production *and* farmers' resource levels.

**Paper 5: Is Sustainable Development Based on Agriculture Attainable in Kenya?
A Multi-disciplinary Case study of Murang'a district** (co-authored with Per Knutsson and Mira Ovuka)

This paper is based on joint multidisciplinary work and investigates whether, and under what conditions, sustainable development based on agriculture is attainable in Murang'a district in Kenya's Central Highlands. The question is relevant in view of Kenya's recent development characterized by massive soil erosion and declining soil fertility (Lewis, 1985; Ovuka, 2000), land fragmentation, fluctuating agricultural production, widespread poverty, rapid population growth and urban expansion, corruption and ethnic tension (Simatei, 1996; Kibwana *et al.*, 1996). Clearly, Kenya's development challenge is to reverse these negative trends and promote sustainable

development. The topic is important since it is necessary to increase the knowledge of the driving forces behind Kenya's negative resource trends and shed light on the links between the key development factors in the search for viable and sustainable solutions.

The study uses multiple analytical approaches in order to address the issues above. First, soil sample analysis to identify on-farm soil nutrient status; second, analysis of aerial photographs to identify land use changes across time (between 1960 and 1996); third, farm analysis of yield and cultivation patterns to identify crop productivity; fourth, in-depth semi-structured interviews among a smaller group of farmers to obtain information on the local land-use history and to elicit their attitudes towards the national soil and water conservation program; and fifth, data collection based on a questionnaire survey among 252 farms in order to identify driving forces behind rural-urban migration. This is done by using regression analysis to estimate households' probability of supplying labour to off-farm agricultural work.

Results from the analyses show that: (i) the area has gone through major biophysical changes: bush-area has decreased in favour of coffee and other crops, tree cover has increased, the share of terraced land has decreased, and the uncultivated land area has declined; (ii) crops such as coffee, maize and banana have replaced food crops like millet, sorghum and peas; (iii) the soil concentration of organic C decreases with erosion and increases with good land management; (iv) soil erosion reduces maize yield; (v) better land management increases maize yield; (vi) low purchase prices on coffee, perceptions of corruption and deteriorating extension services hamper investments in soil conservation and productivity gains in agriculture; (vii) farmers diversify their sources of income which functions as a strong driving force to rural-urban migration.

This study concludes by emphasizing the need to promote sustainable and productive land use. This can be achieved by improving extension advice, enhancing ownership and participation in public soil conservation investment programs, and facilitating enabling economic conditions for small-scale agriculture (e.g. increasing access to credits, speeding up crop payments, ensuring timely and affordable access to adequate inputs), investing in rural feeder roads for better market access, and increasing the job

opportunities for farmers during agricultural off-season by e.g. developing the local food processing industry.

To conclude, this thesis has been designed to combine the breadth of analysis given by inter-disciplinary collaboration with soil scientists, physical geographers and anthropologists on the one hand with the rigour and depth inherent in some tools of economic analysis on the other. Paper 1 represents more of the latter while papers 4 and 5 are the most inter-disciplinary. Papers 2 and 3 are perhaps the ones where it has been possible to best integrate the various approaches into a single methodology.

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Optimal Soil Use with Downstream Externalities¹⁰

Anders Ekbohm¹¹

Abstract

Soil erosion and fertilizer run-off cause serious flow externalities in downstream environments through-out the world. Social costs include e.g. loss of health, life and production due to pollution and eutrophication of freshwater resources, reduced life of hydro-power plants, increased turbidity, and degradation of coral reefs and marine resources.

The key optimal control models on soil capital management omit downstream externalities and assume that the individual farmer and society share the same objective function. In the presence of externalities, there is a discrepancy. In this paper the social planner aims at maximizing the profits from agriculture subject to a soil dynamics-constraint and external damage costs caused by downstream contamination from soil and fertilizer leakage. These effects are not considered by the farmer.

Comparative statics analysis shows that factors which promote a low discount rate (tenure security, access to credits, crop insurance etc.) will reduce soil erosion and nutrient leakage and promote accumulation of soil capital. Socially optimal subsidies for soil conservation not only will build-up soil capital and increase on-site crop production, but will also reduce nutrient leakage and soil loss. A charge on fertilizer would reduce fertilizer use and thus reduce the water pollution caused by leakage of inorganic nutrients.

Based on our model results, combined with an extended discussion on policy instruments, we conclude that the government should try to provide incentives, not necessarily to stop soil loss per se (since the farmers will look after their own capital) but to avoid contamination of downstream environments, where the resource users have few opportunities to negotiate with the upstream farmers, who may even be unaware of the problems they cause.

Keywords: optimal control theory, micro analysis of farm firms, resource management

JEL classification: C61, Q12, Q20

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1. Introduction

Soil erosion causes several serious flow externalities in downstream environments.¹² Eroded soil particulates and agricultural run-off carry pathogens like viruses and bacteria into water courses which increase morbidity and mortality among the downstream water users.¹³ Suspended soil particulates cause tetanus among downstream populations. Nitrate from agriculture leaches into downstream water bodies and causes vomiting, diarrhoea, unconsciousness, seizures and even death, mainly among infants¹⁴. Leaching of nutrients from parent soils or chemical fertilizers increase the incidence of toxic algal blooms¹⁵ and eutrophication of downstream water resources (Matson *et al.*, 1997; Ayoub, 1999). This impacts negatively on lake birdlife (Ballot *et al.*, 2004), shellfish and aquaculture (Shumway, 1990), the health and quality of fish populations, freshwater resources, marine ecosystems and public health (Anderson, 1995; Horner *et al.*, 1997). Nutrient leaching into water bodies may also facilitate rapid spread of invasive alien species such as the water hyacinth in Lake Victoria. Pesticides and herbicides aggravate the pollution of downstream drinking water resources (Naidu *et al.*, 1998; Bartram and Chorus, 1999).

Additional flow externalities from upland agriculture include accelerated velocity of surface water run-off and suspension of sediment in water courses. This effect may be substantial: for example, sediment yield from five major catchments in Ethiopia, Kenya, Tanzania, South Africa and Lesotho ranges between 290-1980 tons/km²/year¹⁶. Accelerated surface water run-off increases the formation and spread of downstream scours and gullies and causes floods. Floods increase the number and spread of malaria mosquitoes and other vectors, and the wash-out of pollutants contaminating downstream water resources. Compounded by the build-up of stream

¹² Soil erosion and surface-run off also cause a set of negative *stock* externalities. These include e.g. sedimentation of water reservoirs, hydro-power plants, irrigation and other fresh-water supply structures, river estuaries (build-up of mud banks), and coastal and marine environments, including corals reefs. Although stock externalities can be important we focus in this paper on flow externalities.

¹³ Including helminths like roundworm (*Ascaris*), whipworm (*Trichuris*) and hookworm (*Necator/Ancylostoma*).

¹⁴ Nitrate is converted in the digestive tracts into toxic nitrite. Nitrite causes the “blue baby syndrome” (Methaemoglobinaemia), which impairs the blood’s ability to transport oxygen within the body. This syndrome is particularly common among infants and may cause death (Younes and Bartram, 2001).

¹⁵ E.g. Cyanobacteria (bluegreen algae), dinoflagellates; For reference, Anderson (1995) presents a summary of major harmful or toxic algal species.

¹⁶ Equivalent to 2.9-19.8 tons/ha/year.

beds, floods wash away infrastructure like roads and bridges and cause streams to change course.

Suspended soil particulates hit river estuaries and coastal environments including coral reefs. The sediment reduces coral cover and diversity, increases turbidity¹⁷, which reduces photosynthesis, inhibits coral settlement and increases cover of macroalgae (Fabricius, 2004). Globally, 22% of the coral reefs in 104 countries are classified as at high or medium threat from inland pollution and soil erosion (Bryant et al., 1998). These changes reduce the growth rate of fish stocks and hamper tourism development. Consequently, flow externalities of soil erosion impose substantial economic costs on coastal communities and local tourism operators (White *et al.*, 2000). Additional qualitative social costs of flow externalities include the private and public cost of increased water treatment and loss of work days due to water-borne diseases. Generally, soil loss into water courses violates the downstream water users' fundamental rights to safe water¹⁸.

None of the analytical, inter-temporal studies we cite below that have treated the economics of soil erosion in a dynamic framework have focused at all on the off-site externalities, yet the associated social costs are significant. To illustrate, Smith (1992) reports that the mean annual off-site damage cost¹⁹ to US agriculture due to flow externalities amounts to 4.6 % of the value of that sector's output. In mountainous tropical areas, with erosive soils, the damage could be higher.

The economics of soil management has a long history and dates back to Wilcox (1938) and Bunce (1942). Significant contributions in this field include papers by Burt (1981), McConnell (1983), Barbier (1990), Barrett (1991), Clarke (1992), LaFrance (1992), Goetz (1997), Grepperud (1996; 1997a,b; 2000), Smith *et al.* (2000) and Yesuf (2004). Soil is natural capital and needs to be managed as an integral part of the farmer's (or social planner's) objective function to maximize the long run

¹⁷ Turbidity refers to the mudiness of the water. It measures the water's cloudiness or haziness, and is caused by the scattering of light by particulates suspended in the water. Main particulates include clay and silt from erosion, phytoplankton, re-suspended bottom sediments, and organic detritus from stream and/or wastewater discharges.

¹⁸ "The human right to water entitles everyone to sufficient, safe, acceptable, physically accessible and affordable water for personal and domestic uses" – General Comment No. 15 (2002): The Right to Water, UN Declaration of Human Rights.

¹⁹ External costs pertaining to freshwater and marine recreation, water storage, navigation, flooding, irrigation, commercial fishing, municipal water treatment, and municipal and industrial use.

private (or social) net profits from agricultural production. In the analytical formulation of this problem, the researcher can assume, as we do, that a farmer uses resources to enhance soil properties, thereby making it a renewable natural resource. See the special cases of LaFrance (1992), Grepperud (1997a,b) and Goetz (1997).

It is instructive to observe how choices for steady state soil quality, labour, fertilizer and perhaps other inputs will respond to changes in parameters such as input and output prices [LaFrance (1992), Grepperud (1997ab) and Goetz (1997)]. Although a formal comparative statics analysis was not conducted, Barrett (1991) demonstrates its importance for policy analysis when he shows that an increase in output price may very well have no or little effect on soil conservation. In fact it can go either way. Barrett points out that this conclusion is completely at odds with public policies designed to change output price in order to (indirectly) reduce the rate of soil depletion. The rate of soil depletion can depend on imperfections in the product and input markets, a subject addressed by others including Yesuf (2004) and McConnell (1983) who introduced labour market imperfections and/or tenure uncertainty. Of the cited soil studies, only LaFrance (1992), Grepperud (1997a,b) and Goetz (1997) feature both comparative statics analysis and a renewable resource in their soil quality model.

All of these studies have at their core, a concern for the loss of the natural capital that soil represents to the farmer. However there is a concern that public bodies (from colonial administrations to current governments and donors) have exaggerated this. There is even something unseemly over the enormous energy put into preventing *future*²⁰ losses for poor farmers in many developing countries – and for whom there is typically not much provision of relatively more useful amenities such as roads, electricity, safe water, health and schooling etc. With security of land tenure (and a well-functioning economy in other respects) the value of the soil should already be internalised by the farmer. This literature helps (among other things) show how detrimental insecure land tenure is since it can lead to low conservation incentives. There are places however where soil erosion/conservation is fairly low on the farmers' agenda since they have very deep fertile soil but hardly any other assets.

²⁰ The idea of preventing soil loss must be to reduce future losses in income.

Soil erosion can however still be a large problem for people living downstream²¹. We contribute to the literature by developing a model which incorporates the downstream social consequences of upstream private decisions. We further discuss appropriate policies for managing off-site effects such as regulation, taxation, subsidies or markets for ecosystem services.

The paper is organized as follows. Section 2 presents a simple generic optimal control model of crop production with flow externalities and soil dynamics. Section 3 analyses comparative statics of the model by identifying and discussing effects of changes in some policy variables. Section 4 includes a summary and some policy conclusions.

2. An Optimal Control Model of Soil Management with Downstream Damage

Assume that agricultural production is determined by the following production function:

$$(1) \quad Q = f(S, L_Q, F)$$

where agricultural output (Q) is a function of soil capital (S), labour supply to agricultural production (L_Q), and chemical fertilizer (F). Output may consist of the value of one or several crops. Although soil is a heterogeneous resource, which consists of several properties, the present model treats soil as a single, one-dimensional variable. While recognizing that soil capital consists of a range of biological, physical and chemical properties²², soil depth is critical for adequate root-holding capacity and other soil properties necessary for good plant growth (Thomas, 1994). Let (S) represent an overall index of soil capital. It is an abstraction, but serves as a proxy for the soil properties, which make up the total capacity of soil to produce

²¹ For instance, in the high-potential areas of Kenya's highlands farmers are endowed with deep fertile soils. At the same time these farmers are so poor that most of their attention goes to immediate problems of satisfying basic needs.

²² For instance, macro nutrients (e.g. nitrogen, phosphorus, potassium), micro-nutrients (e.g. copper), cat-ion exchange capacity, moisture, permeability, structure, clay-sand-silt content and pH-level. See Ekbohm (2007) for further discussion of the many dimensions actually involved in S .

output. $f(S, L_Q, F)$ is assumed to be well-behaved²³. Specifically, in order to identify the effect of changes in policy parameters on the steady state values of the key variables we assume that $f(\cdot)$ is concave; it is increasing in each of its arguments: $f_S > 0, f_{L_Q} > 0, f_F > 0$ (the subscripts indicate the partial derivative with respect to the variable) and subject to diminishing marginal returns, $f_{SS} < 0, f_{L_Q L_Q} < 0, f_{FF} < 0$. The Hessian matrix of $f(S, L_Q, F)$ is negative definite: $f_{LL} f_{SS} - f_{LS}^2 > 0$, $f_{SS} f_{FF} - f_{SF}^2 > 0$, $f_{LL} f_{FF} - f_{LF}^2 > 0$ and $f_{LL} f_{SS} f_{FF} + 2 f_{LS} f_{SF} f_{LF} - f_{SS} f_{LF}^2 - f_{FF} f_{LS}^2 - f_{LL} f_{SF}^2 < 0$. We also assume that $f_{ij} > 0; i, j = S, L_Q, F; i \neq j$.

The typical setting for our model is a developing country where small-scale farming is practiced on steep slopes under erosive tropical rains. The cultivation is not mechanized and depends on family labour. We assume technology to be constant. The household's main cash expenditure on farming inputs includes chemical inorganic fertilizers, used to boost crop production and compensate for nutrients losses due to soil loss.

We introduce the following soil dynamics:

$$(2) \quad \dot{S} = g(L_C) - \psi(L_Q) + \sigma,$$

where change in soil capital, $dS/dt = \dot{S}$ is a function of labour supply to soil conservation (L_C), to agricultural production (L_Q) plus the natural rate of net soil accretion or erosion, σ . Based on empirical evidence, it is reasonable to assume that $g'(L_C) \geq 0, g''(L_C) \leq 0, \psi'(L_Q) \geq 0$ and $\psi''(L_Q) \geq 0$. Labour used for soil conservation is assumed to build up soil capital, although at a diminishing rate. Labour used for cultivation is assumed to depreciate soil capital. Cultivation practices like plowing and seed-bed preparation typically break the soil's physical structure,

²³ Focus in this paper is not on stability or uniqueness of equilibria, nor are we interested in special cases such as corner solutions. We assume functions sufficiently well-behaved to give interior solutions.

accelerate volatilization of nutrients, and increase the soil's susceptibility to erosion (Morgan, 1986; Troeh *et. al.* 1991; Thomas, 1994). An additional assumption is that $\sigma = 0$, which implies that natural soil accretion and natural soil erosion balance out to be zero or negligibly small in the relevant time period. The latter assumption is an approximation but may be reasonable given two facts: first, natural soil accretion is a very slow process; second, soil loss on virgin lands is very small²⁴.

To operationalize the distinction between the farmer's and the social planner's objective function—and focus on the point that soil erosion and surface run-off cause substantial downstream damage, we introduce the following cost function that captures the relationship between downstream environmental quality and soil dynamics:

$$(3) \quad E = b[\dot{S} - \Phi(F)] = b[g(L_C) - \psi(L_Q) + \sigma - \Phi(F)]$$

in which downstream environmental quality (E) is a function of the flow of eroded soil ($b\dot{S}$) $b > 0$, the net soil accretion, and run-off (or leaching) of chemical fertilizers ($\Phi(F)$). E is a placeholder for off-site damages to the quality of downstream environmental resources like rivers, lakes and reservoirs used for drinking-water supplies, marine coastal waters and coral reefs. Following our earlier assumptions, $E_{L_C} > 0$, which implies that enhancing the soil's physical, chemical and structural properties through soil conservation reduces the risk of soil erosion and downstream damages. This is in accordance with research findings by e.g. Troeh *et. al.* 1991. Moreover, a marginal increase in labour supply to agricultural production increases soil erosion, and increases the flow externalities of suspended soil particles in downstream water resources ($E_{L_Q} < 0$), and increased use of chemical fertilizers contributes negatively to the quality of downstream water resources due to surface run-off ($E_F < 0$).

²⁴ Mature forest-, bush- or grass-lands typically offer very dense ground cover and cause minimal soil loss. It is cultivation that breaks up the soil and triggers the accelerated soil erosion process (for a comparison between soil loss on natural lands and bare (cultivated) plots see e.g. Thomas, 1994, Table 5.6, p. 144).

Given a certain technology, the social planner's objective function is to maximize the discounted net social profit (π) from agricultural production over an infinite time horizon²⁵:

$$(4) \quad \pi = \int_{t=0}^{\infty} [pQ - w(L_C + L_Q) - vF + b(\dot{S} - \Phi(F))] e^{-rt} dt .$$

(p), (v), (w) and (r) are given parameters representing the price of output, fertilizer, labour and the discount rate, respectively.

Using Pontryagin's Maximum Principle (Pontryagin *et. al.*, 1964), maximizing equation 4 subject to equations 1-3 is done by maximising the following current value Hamiltonian (H):

(5)

$$H = pf(S, L_Q, F) - w(L_Q + L_C) - vF + \lambda(g(L_C) - \psi(L_Q) + \sigma) + b(g(L_C) - \psi(L_Q) + \sigma - \Phi(F))$$

where λ is the co-state variable.

Assuming an interior solution, the first order necessary conditions for equation 5 are:

$$(6) \quad \frac{\partial H}{\partial F} = 0 \Rightarrow pf_F = v + b\Phi'(F),$$

$$(7) \quad \dot{\lambda} - r\lambda = -\frac{\partial H}{\partial S} = -pf_S,$$

$$(8) \quad \frac{\partial H}{\partial L_Q} = 0 \Rightarrow pf_{L_Q} = w + (b + \lambda)\psi'(L_Q), \text{ and}$$

$$(9) \quad \frac{\partial H}{\partial L_C} = 0 \Rightarrow (b + \lambda)g'(L_C) = w.$$

²⁵ The profit function of the private farmer (π_p) takes the following form:

$\pi_p = \int_{t=0}^{\infty} [pQ - w(L_C + L_Q) - vF] e^{-rt} dt$. Both profit function and its solution can be seen as a special case of the social function analysed for the value $b=0$.

The necessary conditions have familiar interpretations. Equation 6 requires factor market equilibrium; the value of the marginal product of fertilizer (pf_F) should equal its private marginal cost (v) plus the marginal social downstream cost ($b\Phi'(F)$). Rearranging equation 7 into the following expression: $r = \dot{\lambda}/\lambda + pf_S/\lambda$ yields the standard arbitrage equation in capital theory, the competitive rate of return earned for holding any other asset of equivalent risk (r), should at all times equal the return on soil capital due to price appreciation or depreciation ($\dot{\lambda}/\lambda$) plus the real yield from soil capital in production (pf_S/λ).

Equations 8 and 9 introduce some new information pertaining to downstream flow externalities compared to earlier studies on optimal soil use. According to equation 8, the value of the marginal product (VMP) of labour in agricultural production (pf_{L_Q}) should in equilibrium equal the market wage rate (w) plus two marginal contributions: downstream flow damages ($b\psi'(L_Q)$) and the shadow value of soil depletion ($\lambda\psi'(L_Q)$). Equation 9 implies that the marginal social downstream benefit of soil conservation ($bg'(L_C)$) plus the marginal effect on *in situ* soil capital of conservation ($\lambda g'(L_C)$) should in equilibrium equal the market wage rate (w).

In steady state equilibrium, when neither stocks nor prices change, $\dot{S} = \dot{\lambda} = 0$. Then from equation 2,

$$(10) \quad g(L_C) + \sigma = \psi(L_Q),$$

which implies that soil conservation and the labour devoted to it, adjusted for natural changes (σ), should be sufficient to offset loss of soil capital from cultivation.

Moreover, in steady state the sign of $\frac{dL_C}{dx}$ equals the sign of $\frac{dL_Q}{dx}$ (where

$x = r, w, v, p$) since by total-differentiating equation (10) above we get $dL_C = \frac{\Psi'}{g'} dL_Q$.

Further, in steady state equilibrium, according to equation (7),

$$(11) \quad \lambda = \frac{pf_s}{r},$$

which says that the rental rate of soil capital (λ) should equal the capitalized value of the productive future use of this soil (pf_s / r).

3. Comparative Statics – Results and Interpretation

Using comparative statics we derive how marginal changes in policy parameters affect some key variables relevant to the farmer's production as well as the flow externalities. The policy parameters considered are the interest rate (r), wage rate (w), fertilizer price (v), and crop price (p). The derivations of the comparative statics results are contained in Appendix 1 and are summarized in Table 1.²⁶

Table 1. Comparative statics of changes in policy variables

Change in	Effect on		
	Soil (dS)	Labour (dL _C ; dL _Q)	Fertilizer (dF)
Interest rate (dr)	< 0	< 0	< 0
Wage rate (dw)	?	< 0	?
Fertilizer price (dv)	?	< 0	< 0
Crop price (dp)	?	> 0	?

? = Sign undetermined

The most transparent and unambiguous comparative statics results arise from a change in the interest rate. Similar to the findings in e.g. McConnell (1983), Barrett (1991) and LaFrance (1992), when there is a permanent and unanticipated increase in the interest rate, soil capital is reduced because increasing returns on rival capital

²⁶ The results apply for a general production function. By imposing restrictions, further results can be obtained. For example, a Cobb-Douglas production function implies that $dF/dp > 0$.

require disinvestment in soil capital in order to increase its marginal productivity. A difference in the results obtained in this study compared to earlier similar studies, indicate that the inclusion of off-site impacts in the objective function reinforces this effect. In other words, a reduction in the interest rate will result in indirect additional benefits in terms of reduced downstream externalities. Note that these effects are tied to soil stock changes that only occur along the transitions from one steady state to another.

Naturally, factor demand decreases when its own price increases. Whether factor demand increases or decreases when another factor price increases depends on the strength of the substitution effect increasing demand compared to the output effect decreasing factor demand. The net result depends on the production technology. In the presence of a strictly concave Cobb-Douglas production technology, the quantity of factor i decreases when the price of factor j increases because the output effect dominates the substitution effect. In our case the comparative static results are made more complicated by the feedback phenomenon induced by the soil dynamics equation (2). The sign for dS/dw , dS/dv and dF/dw is ambiguous for the following reason. When the wage rate changes, say increases, a decrease in L_Q decreases soil loss and increases S . It also decreases conservation labour and S along with it.

Without putting further structure on the technology, the sign of dS/dw is therefore indeterminate. More quantitatively, as can be seen in Appendix 1 (eq. 20), the sign of

$\frac{dS}{dw}$ is ambiguous since we cannot determine *a priori* whether $\left(\frac{g''}{g'}\Psi' + \Psi''\right) > 0$

or ≤ 0 . $\frac{dS}{dw} < 0$ if $\frac{g''}{g'}\Psi' + \Psi'' \geq 0$ or $\left|\frac{g''}{g'}\right| \leq \left|\frac{\Psi''}{\Psi'}\right|$, i.e. if soil conservation labour

exhibits less curvature than the negative impact on soil capital of cultivation labour.

There is a similar effect for dS/dv . When the price of fertilizer changes, say increases, the substitution and output effect play out in some fashion with respect to S and L_Q . However, the change in L_Q causes S to move in the opposite direction via the soil dynamics equation and further contributes to the indeterminacy we observe.

The feedback forces, due to the soil dynamics equation, contribute further to the ambiguous sign of dF/dw . Should w increase, there is the negative output effect together with the positive substitution effect for S and L_Q . These changes transmitted to the soil dynamics equation individually influence S in an indeterminate fashion, which then affects the endogenously determined shadow price of S in an indeterminate manner. How F ultimately equilibrates is affected by the new price ratio, λ/w . Similarly, the sign of the effect of an increase in crop price on fertilizer use is undetermined, since we cannot sign $(g''/g')\Psi' + \Psi''$. However, a wage increase negatively affects fertilizer use $\left(\frac{dF}{dw} < 0\right)$ if $\frac{g''}{g'}\Psi' + \Psi'' \geq 0$ or $\left|\frac{g''}{g'}\right| \leq \left|\frac{\Psi''}{\Psi'}\right|$ (for details, see eq. 17 in the Appendix). As before, the wage effect is positive if soil conservation labour is less elastic than cultivation labour.

dS/dp is ambiguous because when productive labour increases because p increases, this decreases S in the soil dynamics equation, that offsets to an unknown amount the positive effect of a positive product price change on S . Although his model assumptions are slightly different²⁷, Barrett (1991) obtains a similar result. He finds that the sign of the effect on soil conservation and soil depth of an increase output price is indeterminate, unless one makes specific assumptions about the technical relationships and dependence between soil, soil loss attributable to cultivation, soil conservation and non-soil inputs (viz. fertilizers).

A relevant question which follows from the comparative statics results is why there is a negative effect of fertilizer price (v) on labour use? Arguably, the result is created by two effects. First, we have two opposing forces: as v increases there is *substitution* out of fertilizer into the other factors, so labour use goes up and soil capital (S) should go up too. Familiarly, the *output effect* caused by the fact that fertilizer is now more expensive induces labour to decrease and S should go down too. Second, S too changes through the feedback in the soil dynamics equation through changing labour use (both cultivation and conservation). Apparently, the output effect, combined with the soil dynamics feedback effect, dominates the substitution effect.

²⁷ For instance, Barrett uses a Cobb-Douglas production function, and assumes that farmers choose the amount of soil loss directly in their production; the cost of labour is not included.

Policy Instruments to Mitigate Downstream Effects

Most analyses of soil loss have a limited focus on policy instruments, which address on-farm concerns. Given our model and the comparative statics results, we discuss policy instruments below in an environment where there are off-site externalities. The key question facing the social planner is thus: what (mix of) policy instruments enables the government to maximize the discounted social profit from agricultural production subject to downstream externalities caused by soil erosion and fertilizer run-off. The policy maker may choose between a large set of policy instruments such as (i) direct regulation, (ii) information, (iii) property rights, (iv) charges and (v) subsidies²⁸. In the choice of relevant policy instruments it is important to also consider issues regarding rights, fairness (distributional and equity concerns), efficiency and administrative feasibility (Stern, 2003). Although the specific (historical, social or political) context may prevent real implementation of some policy instrument(s) presented below, it is nevertheless possible and useful to discuss the experiences and the pros and cons of these instruments in a developing country perspective.

(i) Direct regulation: Theoretically, direct regulation would imply that farmers were obliged to supply cultivation labour, fertilizer and soil conservation labour corresponding to their respective socially optimal levels (given by eq. 6, 8 and 9). Although the privately and socially optimal levels of soil conservation differ, governments have frequently used direct regulation (in terms of cultivation bans, certain soil conservation requirements etc.) as a policy instrument to address soil erosion and run-off (Hudson, 1981; Morgan, 1986). Kenya is no exception in this respect. Soil conservation was made compulsory on cultivated land in 1937. Until Independence in 1963, implementation of soil conservation among the native African farmers relied on government orders, regulation, coercion and penalties. Mandatory engineering solutions, such as construction of labour-intensive bench terraces, cut-off drains, stone gabions and retention ditches, were prescribed (Kimaru, 1998).

²⁸ Due to lack of practical experiences, the complexities and the substantial institutional requirements associated with use of other policy instruments, like tradable permits (for reference, see Stern (2003)), they are not considered in this paper.

Although the choice and implementation of policies have changed considerably since Kenya's independence, regulation is still an important element of the country's soil conservation efforts. Farmers are required by law to conserve their soil. Based on specific soil conservation requirements for different types of land, the local soil conservation officer keeps records of what soil conservation measures individual farmers have to establish. Failure to establish these measures subjects them to an elaborated set of graduated sanctions. Other examples of regulatory command and control measures pertaining to soil use in Kenya include bans on cultivating soils above certain hill slopes (>60%) or along river-banks, or vertical ploughing (perpendicular to the contour). Due to population pressure, lack of knowledge, insufficient enforcement and other reasons, these bans are frequently violated.

However, the regulatory approach to soil conservation has largely been unsuccessful. The underlying cause can be found in the farmer's incentive structure. Our model shows that a privately rational farmer would only conserve soil up to the point where the marginal benefit on *in situ* soil capital of conservation ($\lambda g'(L_C)$) equals the market wage rate (w). In the normal case, the marginal social downstream benefit of soil conservation ($bg'(L_C)$) will not be internalized in the farmer's economic decision. In other words, a poor farmer who cultivates deep fertile soils on steep slopes and is constrained in labour and cash, has for rational reasons small incentives to prevent *all* soil loss and fertilizer run-off from his/her land. Conserving *all* soil implies that the farmer will bear the full social cost of soil conservation and preventing downstream damages, whereas only a share of the benefits accrue privately. Since the marginal social downstream benefit of soil conservation ($bg'(L_C)$) is essentially public, a rational resource-constrained farmer will not (or cannot be expected to) pick up the cost of attaining it. Similarly, poor farmers cannot be expected to prevent the public downstream flow damages ($b\psi'(L_O)$). Thus farmers continue to produce public bads in terms of degradation of downstream water resources, siltation, sedimentation and pollution. In contrast to the individual farmer's financial reasons, the social planner has a strong *economic* reason to encourage full soil conservation, discourage soil erosion and prevent downstream damages.

(ii) Information: Increasing the knowledge among farmers has frequently been used by governments to promote sustainable agriculture. In Kenya, this has been pursued by disseminating the benefits of soil conservation and costs of soil loss, and provision of practical extension advice to small-scale farmers on how to conserve soil and attain sustainable land husbandry. These activities have largely replaced earlier land use-policies based on coercive regulation. Since 1974, farmers have been offered specific SWC field training, study visits to research stations, on-farm advice by soil conservation extension officers and educational material in a National Soil and Water Conservation Programme (NSWCP). Farmers have been organised into Catchment Planning Teams with the purpose of conserving soil in a coherent manner in designated geographical areas (Admassie, 1992; OPTO, 2006).

In general, information can be a cost-effective policy instrument for environmental management (Sterner, 2003). Kenya's government's use of information to increase soil conservation implementation has been rated rather successful (OPTO, 2006; Kimaru, 1998; Lundgren, 1993)²⁹ and Kenya's farmers have voluntarily increased their soil conservation efforts, quantitatively as well qualitatively. However, downstream damages due to soil loss and fertilizer run-off remain a large problem. This indicates that traditional information on soil conservation technologies is a useful but insufficient policy instrument to *fully* prevent soil erosion and downstream damages.

The reason to this lies in the individual farmer's objective function. The farmer's objective is to maximize private discounted profits (π_p) without considering external effects (see footnote 16 for details). It is true that L_C and L_Q embody skills obtained *inter alia* from the government's NSWCP but this knowledge mainly assists farmers to fulfil their private objectives. Hence, increased information cannot be expected to produce *socially* optimal outcomes. In other words, π_p excludes off-site damages and increasing the amount of information to farmers does not alter the fundamental economic incentives driving their behaviour. Another complication regarding information is the fact that identifying and disseminating the specific downstream effects caused by individual farmer's agricultural production is also very difficult in

²⁹ The positive effects of extension advice have been contested by Evenson and Mwangi (2001) and Gautam and Anderson (1999), who found limited evidence of significant positive effects on farmers' agricultural productivity of Kenya's Training and Visit system for agricultural extension services.

cases characterized by non-point source pollution and geographically remote externalities.

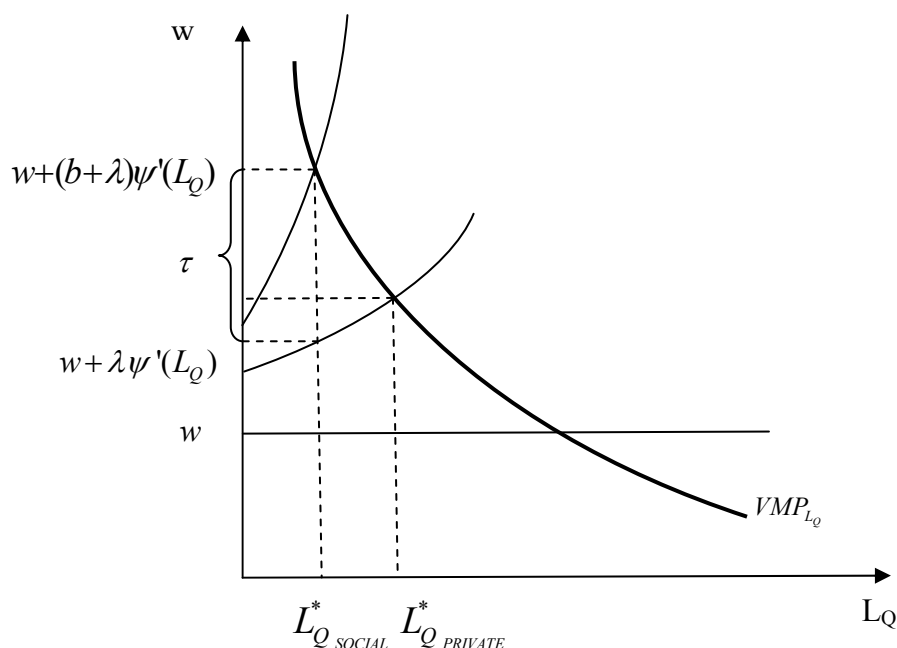
A complementary policy instrument would be to increase farmers' knowledge on public investments and development plans. Our comparative statics result regarding the interest rate ($dS/dr < 0$) suggests that increasing farmers' knowledge on public measures, which reduce farmers' discount rate (e.g. input-/output market development plans, road investments, land tenure reforms etc.), has positive effects on soil capital formation and indirectly prevents downstream damages. Moreover, information on downstream effects from agriculture is highly relevant for the social planner in fulfilling its objective function, and in the design of economic policy instruments (such as charges, fees, subsidies), which can be used to curb the externalities.³⁰

(iii) Charges or fees: In principle, the external costs imposed on downstream victims should be internalized into the farmers' production costs. The Pigouvian approach would be to put a charge or a fee on the degrading inputs (or practices). Illustrated in figure 1 below, a rational farmer (with secure rights) would use cultivation labour such that VMP of L_Q equals the market wage for labour plus the marginal effect on soil capital ($\lambda\psi'(L_Q)$). This corresponds to $L_{Q\text{ PRIVATE}}^*$. However, since cultivation labour depreciates soil and cause downstream flow externalities (represented by $b\psi'(L_Q)$), it is socially optimal to reduce the use of cultivation labour to $L_{Q\text{ SOCIAL}}^*$. Reducing erosive cultivation labour could in principle be achieved by coercive measures e.g. restrictions on how much labour one can use (on a given plot of land) for agricultural production with, however, the attendant problems of monitoring and enforcement.

Introducing textbook economic incentives, one can instead introduce a charge, τ , corresponding to $b\psi'(L_Q)$ in equation 8. In practice, this is however also hard to enforce but some more realistic policies to manage downstream externalities are discussed later.

³⁰ In special cases where *payments for ecological services* (see sub-section (v) below) may be obtained, information of downstream costs of soil loss or social benefits of soil conservation, may be strategically important knowledge to individual farmers as well in order for them to take advantage of this financial benefit.

Figure 1. Agricultural Labour Demand – the Effect of a Pollution Charge



Regarding fertilizer, from (6) we know that a privately rational farmer would use fertilizer in such an amount that VMP_F equals the fertilizer price ($pf_F(S, L_Q, F) = v$). However, since fertilizer use also produces a negative externality ($b\phi'(F)$), the government ought to introduce a charge or a fee which internalizes this social cost. Would this be a viable policy instrument to achieve the social planner's objective function? As shown by the comparative statics results (in Table 1), raising the farm-gate price of fertilizer, through a charge or a fee, reduces fertilizer use ($\frac{dF}{dv} < 0$) and thus the nutrient run-off into water systems.

However, a charge on downstream pollution is problematic for several reasons. Firstly it is politically very sensitive. Farmers may be rich and powerful or – as in many tropical countries so poor that they can hardly support additional taxation. In principle it might be possible to construct a package in which increased fertilizer taxes are counteracted by lowering other taxes for instance on their output. Introducing a tax or a charge on erosive cultivation would however also be infeasible for monitoring and enforcement reasons. Soil erosion is typically a non-point source pollution problem,

which originates in vast watersheds and is caused by thousands or even millions of small-scale farmers' agricultural production. A pure downstream pollution tax would be infeasible since there is insufficient monitoring ability. Joint schemes to make farmers collaborate in reducing pollution are possible but much more complex. One component of the pollution – that which comes from commercial fertilizers - could of course be taxed.

Irrespective of whether a fertilizer charge is targeted at farmers by an *ad valorem* tax or directly at the producers, a fertilizer charge increases the farmer's production costs, reduces their profits, and will therefore be severely resisted. It may also be thought of as running counter to policies designed to improve food security and self sufficiency.

It may be argued that a fertilizer tax can be used to subsidise conservation labour (L_C)? Combining these two policy instruments is however difficult basically for reasons of efficiency. Recall that our model says: i) to tax fertilizer use a very specific amount to achieve efficiency, ii) there is a very specific amount of subsidy for L_C to achieve efficiency. To ensure efficiency, one has to keep these two policies separate. In practice that may be difficult. If you explicitly tie one policy to the other, then farmers have an incentive to distort their behaviour. The farmer might strategically use more fertilizer (which increases private yield but causes downstream damages) in order to increase the "subsidy fund" for his/her conservation labour. So formally one has to keep efficiency decisions separate from financing decisions.

(iv) Property rights: Enhancing property rights is a policy instrument, which implicitly reduces farmers' discount rate. Land ownership security affects both investment incentives and the availability of resources to finance investments (Feder and Feeny, 1991). Farmers holding title deeds to their land may use it as collateral for credits, which enable land investments such as terracing or tree plantation. In a case study of northern Ethiopia, land tenure security was positively associated with soil conservation investments (Alemu, 1999). Feder and Onchan (1987) find that land-improving investments are positively affected by ownership security.

Recalling the comparative statics results, reduced interest rates builds up soil capital ($dS/dr < 0$), increases labour supply to soil conservation ($dS/L_C > 0$) and thus reduces

downstream externalities. In Kenya's Central Highlands land tenure security is relatively high compared to e.g. its neighbouring countries. A majority of the smallholders hold title deeds to surveyed, registered and adjudicated land, which can be sold or bought in an open market. The title deeds prevent arbitrary evictions and facilitate bank loans. However, as land fragmentation accelerates due to population growth and sub-division of farms, the government has an important role to play. Traditionally, land is owned by men and inherited by sons. Women who head households, divorced women or widows enjoy no rights to hold land or obtain a title deed to their specific plot. Consequently, they have little incentives to invest in land they cultivate. This introduces distortions in the land market and reduces the tenure security. An important policy measure is thus to adjust the current institutions governing land ownership with respect to the existing distortions, and e.g. facilitate registration of sub-divided land and strengthen women's rights to own, buy and sell land, and use land as collateral for credits.

Strengthening on-farm tenure security is necessary but as our model shows insufficient to fully prevent downstream externalities. A complementary measure would be to strengthen the human right of downstream inhabitants to clean water. These users' right to clean water needs to be acknowledged, formally defined, clarified and enforced. This implies a responsibility on the government to increase the provision of clean water, through e.g. intensifying the support to soil conservation, decontamination of existing water sources, redistribution among existing users/sectors, and/or increasing the supply from other freshwater sources.

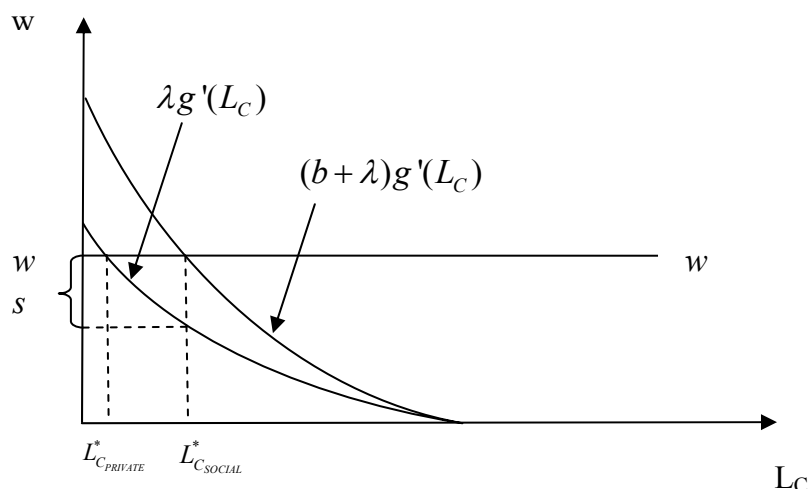
Regarding equity and rights the critical question is who is entitled to what right? Are downstream water users entitled to clean water, or do the upstream farmers hold the right to pollute? It seems natural to argue that all downstream victims should be compensated (by the polluters) for the damage inflicted on them. However, the problems pertaining to soil erosion, sedimentation and nutrient leakage are typically characterized by asymmetric information, and direct compensation between all polluters and victims implies very high transactions costs. Moreover, in Kenya's highlands and in many other similar situations in developing countries, up-land farming started long before downstream hydro-power production, irrigation and coastal tourism were initiated. Although soil conservation was mandatory in Kenya

(and other East African countries) under the British colonial rule, it was never fully enforced. It has become more and more an accepted fact that soil loss naturally occurs as an unintended negative side-effect of resource-constrained small-scale farming on erodible soils in tropical hilly environments. The farmers can thus claim a historical prescriptive right to pollute. It may thus be argued that the more recent downstream economic activities (hydro-power, irrigation etc.) had an obligation - prior to their investments - to properly internalize the cost of environmental inputs (including polluted water) in their production and ensure adequate protection against it.

Regarding poor people, who reside in the downstream areas and depend on the water resources for their livelihood, the equity and rights issues lead to another conclusion. This group is financially and politically much weaker than the hydro-power companies, tourism operators etc. Typically, they settled in the low-land area before the high-land farmers settled in theirs (Ochieng and Maxon, 1992). As farming has become more intensive and expanded into virgin mountain forests, sedimentation of the water resources on which they depend has increased. Hence, unanticipated at the time of settlement they have become victims of increasing water pollution. As opposed to the hydro-power companies and other commercial operators, they lack capital for pollution protection and prevention. It may thus be argued that they are entitled to some compensation.

(v) Subsidies and Payments for Environmental Services: Subsidies have the advantage of introducing a positive incentive to encourage a desirable action. As illustrated in figure 2 below, a competitive farmer would build up soil by using soil conservation labour in an amount such that the private marginal value of conservation labour, $(\lambda g'(L_C))$ equals the market labour wage rate (w). This corresponds to $L_{PRIVATE}^*$, which however is too little to prevent downstream flow externalities. A farmer who behaves altruistically and conserves more soil than the privately optimal amount produces environmental public goods to society $(bg'(L_C))$. For society to encourage soil conservation up to the socially optimal level (L_{SOCIAL}^*) , the farmer would need some form of compensation or a financial transfer (s), which corresponds to this level.

Figure 2. Conservation Labour Supply and the Effect of Wage Subsidy



Historically, subsidies to soil conservation have primarily been provided to prevent private yield losses³¹. Given the negative externalities inflicted on downstream populations, the government may create new property rights and decide that the downstream population has the right to clean water, the coastal population has the right to coral reefs, etc. From these rights *Payments for Environmental Services* (PES) ensue.

PES have emerged as a new innovative policy instrument to encourage soil conservation and reduce downstream externalities (Pagiola and Platais, 2002; Gutman, 2003). Essentially *PES* is a subsidy, but ensues from established property rights and presupposes a broader (social) scope to soil erosion and soil conservation. In our case, provision of *PES* implies that farmers who conserve soil are compensated for public environmental services³² they provide to society.

Although a soil conservation subsidy in terms of *PES* does not cause the same win-lose effect as fertilizer charges³³, it has both pros and cons: in our case, *PES* might work if it functions as a real incentive for farmers to conserve soil beyond the

³¹ For example, Kenya’s government has provided subsidies in kind (e.g. tree seedlings, tools, implements) and in cash payments to encourage farmers to conserve soil in order to maintain crop yields and sustain food self-sufficiency.

³² Environmental services such as protecting freshwater quality, controlling hydrological flows, reduced suspension and sedimentation of water systems, prevention of floods and landslides, biodiversity conservation and carbon sequestration.

³³ Pollution reduction is attained at the expense of reduced crop production.

privately optimal level ($L_{C_{PRIVATE}}^*$) up to the socially optimal level ($L_{C_{SOCIAL}}^*$). The social costs are mainly associated with the revenues necessary to cover the payments. Subsidies increase the government's public expenditures and therefore have to be used with care. This is particularly relevant in developing countries, which are typically constrained by a very limited budget envelope. PES may work in situations where the incentives are compatible for both service users (downstream victims) and service providers (upland farmers), where transaction costs are low, and where the benefits of the environmental services equal or exceed the costs to the service providers (Landell-Mills and Porras, 2002; Pagiola *et al.*, 2002, 2005). Other critical issues in implementing PES include (i) the characterization of the ecological services, (ii) the establishment of sustainable financing mechanisms, (iii) the design and implementation of effective payment systems, and (iv) the establishment of adequate institutional frameworks (Campos *et al.*, 2005).

4. Summary and Conclusions

Agricultural production pursued by small-scale farmers on hillsides of developing countries commonly causes downstream damages due to soil erosion and nutrient run-off, which reduce society's total welfare. This problem is addressed in an optimal control model, in which a social planner maximizes the social profits from farmers' agricultural production subject to external damage costs and a soil dynamics-constraint. These downstream effects, omitted in other formal models, are substantial and presuppose that the individual farmer and the social planner share the same objective function. In our case with externalities, this is not true.

In the world of a strictly concave production technology and all factors are substitutes, many of the comparative statics results are routine. Levels of the factors except soil, vary directly with product price and indirectly with own price. Factor demand varies inversely with an increase in the discount rate. Therefore, factors which promote a low discount rate (tenure security, access to credits, crop insurance schemes) are likely to reduce soil erosion, build up soil capital and prevent water pollution from fertilizer run-off.

We expect the output effect of a factor price change to dominate the substitution effect but the results are ambiguous for changes in soil quality induced by changes in the wage rate or fertilizer price and for the impact of a wage change on fertilizer use. The ambiguity arises because of feedbacks stemming from the equation governing soil dynamics. For example, a wage increase should decrease soil capital, but a decrease in productive labour also reduces the intensity of cultivation and increases soil quality.

Further, the analysis shows that an increase in fertilizer price is negatively associated with fertilizer use, and conservation and cultivation labour, respectively. This suggests that a charge on fertilizer yields mixed effects with respect to downstream externalities: a fertilizer charge (i) reduces fertilizer use and thus reduces water pollution from nutrient run-off, and (ii) reduces both soil conservation and labour supply to cultivation. Without further model assumptions, the net impact of (ii) on on-site soil capital or downstream environmental quality cannot be determined *a priori*.

The results also show that an increase in crop price is positively associated with labour supply to soil conservation and cultivation. From the perspective of downstream effects, this result may be interpreted in at least two ways. First, increased soil conservation will build up soil capital and reduce loss of nutrients. Second, increased crop prices will boost the supply of cultivation labour which will accelerate soil loss. Due to these opposite effects on soil capital and downstream damage, it is difficult *a priori* to establish the impact of changed crop prices. If one can establish empirically, that the positive effects dominate, the government ought to increase (implicitly) the farm-gate selling prices by investing in feeder-roads and other factors which reduce farmers' transport and marketing costs.

Due to the ambiguous results of changing the crop and fertilizer prices, we argue that payments for environmental services, targeted at up-stream soil conservation, should be encouraged. Provided that these payments can be financed and enforced, PES would reward socially optimal behaviour by providing an incentive to build up soil capital (which increases output and the value of the land) and reduce downstream negative externalities.

Based on our findings we conclude that the government may play a crucial role in defining appropriate policies and implementing reforms which encourage farmers to maximize society's profits from agricultural production, build up soil capital, prevent soil erosion, and counteract downstream externalities from soil loss and nutrient leakage. Government reforms, which aim at boosting crop production and make use of policy variables like agricultural input prices, crop prices and the interest rate, need also to consider their external downstream effects.

Appendix 1. Comparative Statics Analysis

Use equation (11) in the text to substitute for λ in (8) and (9):

$$(8') \quad pf_L(S, L_Q, F) - w - \left[b + \frac{p}{r} f_S(S, L_Q, F) \right] \Psi'(L_Q) = 0$$

$$(9') \quad \left[b + \frac{p}{r} f_S(S, L_Q, F) \right] g'(L_C) - w = 0$$

Total differentiation of equations (6) (8') and (9'), and total-differentiating equation (10) in the text ($dL_C = \frac{\Psi'}{g'} dL_Q$ used to substitute for dL_C) yields the following system:

$$(15) \quad \mathbf{J} \cdot \mathbf{K} = \mathbf{P} \cdot \mathbf{L}$$

where

$$\mathbf{J} = \begin{bmatrix} pf_{FS} & pf_{FL} & [pf_{FF} - \Phi''] \\ \left[pf_{LS} - \frac{p}{r} f_{SS} \Psi' \right] & \left[pf_{LL} - \left(b + \frac{p}{r} f_S \right) \Psi'' - \frac{p}{r} f_{SL} \Psi' \right] & \left[pf_{LF} - \frac{p}{r} f_{SF} \Psi' \right] \\ \frac{p}{r} f_{SS} g' & \left[\left(b + \frac{p}{r} f_S \right) \frac{g''}{g'} \Psi' + \frac{p}{r} f_{SL} g' \right] & \frac{p}{r} f_{SF} g' \end{bmatrix};$$

$$\mathbf{K} = \begin{bmatrix} dS \\ dL_Q \\ dF \end{bmatrix}; \mathbf{P} = \begin{bmatrix} 0 & 0 & 1 & -f_F \\ -\frac{p}{r^2} f_S \Psi' & 1 & 0 & \left[f_L + \frac{f_S}{r} \Psi' \right] \\ \frac{p}{r^2} f_S g' & 1 & 0 & -\frac{f_S}{r} g' \end{bmatrix} \text{ and } \mathbf{L} = \begin{bmatrix} dr \\ dw \\ dv \\ dp \end{bmatrix}.$$

Given our assumptions on functional form (from Chapter 2), the determinant of matrix \mathbf{J} is positive:

(16)

$$\begin{aligned}
|J| = & \frac{g'p^2}{r} \left[\underbrace{\Phi''(f_{LL}f_{SS} - f_{SL}^2)}_{(+)} - \underbrace{p(f_{LL}f_{SS}f_{FF} + 2f_{LS}f_{SF}f_{LF} - f_{SS}f_{LF}^2 - f_{FF}f_{LS}^2 - f_{LL}f_{SF}^2)}_{(-)} \right] \\
& + p \left[\underbrace{p(f_{FF}f_{SS} - f_{SF}^2)}_{(+)} - \underbrace{\Phi''f_{SS}}_{(-)} \right] \left[\frac{b(g')^2 r \Psi'' + f_S (g')^2 p \Psi'' - f_S g'' p (\Psi')^2 - b g'' r (\Psi')^2}{g' r^2} \right]_{(+)} \\
& - \underbrace{\frac{f_S g'' p^2 \Psi'}{r g'}}_{(-)} \left[\underbrace{\Phi'' f_{SL} + p f_{LF} f_{SF} - p f_{FF} f_{SL}}_{(+)} \right] > 0
\end{aligned}$$

Comparative Statics of the equation system represented by (15) using Cramer's rule is given by (17-28) below:

$$(17) \quad \frac{dS}{dr} = \frac{\begin{bmatrix} 0 & p f_{FL} & [p f_{FF} - \Phi''] \\ -\frac{p}{r^2} f_S \Psi' & \left[p f_{LL} - \left(b + \frac{p}{r} f_S \right) \Psi'' - \frac{p}{r} f_{SL} \Psi' \right] & \left[p f_{LF} - \frac{p}{r} f_{SF} \Psi' \right] \\ \frac{p}{r^2} f_S g' & \left[\left(b + \frac{p}{r} f_S \right) \frac{g''}{g'} \Psi' + \frac{p}{r} f_{SL} g' \right] & \frac{p}{r} f_{SF} g' \end{bmatrix}}{|J|} < 0$$

since the sign of the numerator is negative:

$$\underbrace{\frac{g'p^2}{r^2} f_S f_{LL} \Phi''}_{(+)} + f_S \frac{p^2}{r^2} \left(b + \frac{p f_S}{r} \right) \underbrace{\left(\frac{g'' (\Psi')^2}{g'} - g' \Psi'' \right)}_{(-)} \underbrace{\left(\frac{\Phi''}{p} - f_{FF} \right)}_{(+)} - \frac{f_S g' p^3}{r^2} \underbrace{\left(f_{FF} f_{SS} - f_{SF}^2 \right)}_{(+)} < 0$$

$$(18) \quad \frac{dL_Q}{dr} = \frac{\begin{bmatrix} p f_{FS} & 0 & [p f_{FF} - \Phi''] \\ \left[p f_{LS} - \frac{p}{r} f_{SS} \Psi' \right] & -\frac{p}{r^2} f_S \Psi' & \left[p f_{LF} - \frac{p}{r} f_{SF} \Psi' \right] \\ \frac{p}{r} f_{SS} g' & \frac{p}{r^2} f_S g' & \frac{p}{r} f_{SF} g' \end{bmatrix}}{|J|} < 0$$

since numerator is negative:

$$-\frac{f_S g' p^3}{r^2} \underbrace{\left[f_{LF} f_{SF} + f_{SL} \left(\frac{\Phi''}{p} - f_{FF} \right) \right]}_{(+)} < 0$$

$$(19) \frac{dF}{dr} = \frac{\begin{bmatrix} pf_{FS} & pf_{FL} & 0 \\ \left[pf_{LS} - \frac{p}{r} f_{SS} \Psi' \right] & \left[pf_{LL} - \left(b + \frac{p}{r} f_S \right) \Psi'' - \frac{p}{r} f_{SL} \Psi' \right] & -\frac{p}{r^2} f_S \Psi' \\ \frac{p}{r} f_{SS} g' & \left[\left(b + \frac{p}{r} f_S \right) \frac{g''}{g'} \Psi' + \frac{p}{r} f_{SL} g' \right] & \frac{p}{r^2} f_S g' \end{bmatrix}}{|J|} < 0$$

since the sign of the numerator is negative:

$$\frac{f_S p^2}{r^3 g'} \left[(br + pf_S) \underbrace{\left(g'' (\Psi')^2 - (g')^2 \Psi'' \right)}_{(-)} \underbrace{\left(\frac{\Phi''}{p} - f_{FF} \right)}_{(+)} + pr (g')^2 \underbrace{\left(f_{LL} f_{SF} - f_{LF} f_{SL} \right)}_{(-)} \right] < 0$$

$$(20) \frac{dS}{dw} = \frac{\begin{bmatrix} 0 & pf_{FL} & [pf_{FF} - \Phi''] \\ 1 & \left[pf_{LL} - \left(b + \frac{p}{r} f_S \right) \Psi'' - \frac{p}{r} f_{SL} \Psi' \right] & \left[pf_{LF} - \frac{p}{r} f_{SF} \Psi' \right] \\ 1 & \left[\left(b + \frac{p}{r} f_S \right) \frac{g''}{g'} \Psi' + \frac{p}{r} f_{SL} g' \right] & \frac{p}{r} f_{SF} g' \end{bmatrix}}{|J|} \leq 0 \text{ or } \geq 0$$

since the sign of the numerator is indeterminate:

$$\underbrace{\left(\frac{g''}{g'} \Psi' + \Psi'' \right)}_{(?)} \underbrace{\left(f_{FF} - \Phi'' \right)}_{(-)} \underbrace{\left(b + \frac{p}{r} f_S \right)}_{(+)} - p^2 \underbrace{\left(f_{FF} f_{LL} - f_{SL}^2 \right)}_{(+)} +$$

$$+ \underbrace{p \Phi'' f_{LL}}_{(-)} - \frac{p}{r} (g' + \Psi') \underbrace{\left(pf_{LF} f_{SF} - pf_{FF} f_{SL} + \Phi'' f_{SL} \right)}_{(+)} \leq 0 \text{ or } \geq 0$$

$$(21) \frac{dL_Q}{dw} = \frac{\begin{bmatrix} pf_{FS} & 0 & [pf_{FF} - \Phi'] \\ [pf_{LS} - \frac{p}{r} f_{SS} \Psi'] & 1 & [pf_{LF} - \frac{p}{r} f_{SF} \Psi'] \\ \frac{p}{r} f_{SS} g' & 1 & \frac{p}{r} f_{SF} g' \end{bmatrix}}{|J|} < 0$$

since the sign of the numerator is negative:

$$-\frac{p^2}{r} \left[\underbrace{rf_{LF} f_{SF}}_{(+)} + \underbrace{\frac{r}{p} f_{SL} \Phi''}_{(+)} - \underbrace{rf_{FF} f_{SL}}_{(-)} + \underbrace{\Psi' f_{FF} f_{SS}}_{(+)} + (g' + \Psi') \left(\underbrace{(f_{FF} f_{SS} - f_{SF}^2)}_{(+)} - \frac{\Phi'' f_{SS}}{p} \right) \right] < 0$$

$$(22) \frac{dF}{dw} = \frac{\begin{bmatrix} pf_{FS} & pf_{FL} & 0 \\ [pf_{LS} - \frac{p}{r} f_{SS} \Psi'] & [pf_{LL} - (b + \frac{p}{r} f_S) \Psi'' - \frac{p}{r} f_{SL} \Psi'] & 1 \\ \frac{p}{r} f_{SS} g' & \left[(b + \frac{p}{r} f_S) \frac{g''}{g'} \Psi' + \frac{p}{r} f_{SL} g' \right] & 1 \end{bmatrix}}{|J|} \leq 0 \text{ or } \geq 0$$

since the sign of the numerator is indeterminate:

$$\frac{p^2}{r} \left[\underbrace{rf_{LL} f_{SF}}_{(-)} - \underbrace{rf_{LF} f_{SL}}_{(+)} - \underbrace{\left(\frac{g''}{g'} \Psi' + \Psi'' \right)}_{(?)} \underbrace{(bpr \cdot f_{SF} + f_S f_{SF})}_{(+)} + (g' + \Psi') \underbrace{(f_{LF} f_{SS} - f_{SF} f_{SL})}_{(-)} \right] \leq 0 \text{ or } \geq 0$$

As before, $\frac{dF}{dw} < 0$ if $\frac{g''}{g'} \Psi' + \Psi'' \geq 0$ or $\left| \frac{g''}{g'} \right| \leq \left| \frac{\Psi''}{\Psi'} \right|$.

$$(23) \frac{dS}{dv} = \frac{\begin{bmatrix} 1 & pf_{FL} & [pf_{FF} - \Phi'] \\ 0 & [pf_{LL} - (b + \frac{p}{r} f_S) \Psi'' - \frac{p}{r} f_{SL} \Psi'] & [pf_{LF} - \frac{p}{r} f_{SF} \Psi'] \\ 0 & \left[(b + \frac{p}{r} f_S) \frac{g''}{g'} \Psi' + \frac{p}{r} f_{SL} g' \right] & \frac{p}{r} f_{SF} g' \end{bmatrix}}{|J|} \leq 0 \text{ or } \geq 0$$

since the sign of the numerator is indeterminate:

$$\left(b + \frac{pf_S}{r}\right) \left[\underbrace{\frac{g''p\Psi'}{g'}}_{(-)} \underbrace{\left(\frac{\Psi'f_{SF}}{r} - f_{LF}\right)}_{(?)}, \underbrace{\frac{f_{SF}g'p\Psi''}{r}}_{(+)} \right] + \frac{g'p^2}{r} \underbrace{(f_{LL}f_{SF} - f_{LF}f_{SL})}_{(-)} \leq 0 \text{ or } \geq 0$$

$$\frac{dS}{dv} < 0 \text{ if } \frac{\Psi'f_{SF}}{r} - f_{LF} \geq 0$$

$$(24) \frac{dL_Q}{dv} = \frac{\begin{bmatrix} pf_{FS} & 1 & [pf_{FF} - \Phi'] \\ [pf_{LS} - \frac{p}{r}f_{SS}\Psi'] & 0 & [pf_{LF} - \frac{p}{r}f_{SF}\Psi'] \\ \frac{p}{r}f_{SS}g' & 0 & \frac{p}{r}f_{SF}g' \end{bmatrix}}{|J|} < 0$$

since the sign of the numerator is negative:

$$\frac{g'p^2}{r} \left[\underbrace{f_{SS}f_{LF}}_{(-)} - \underbrace{f_{SF}f_{SL}}_{(+)} \right] < 0$$

$$(25) \frac{dF}{dv} = \frac{\begin{bmatrix} pf_{FS} & pf_{FL} & 1 \\ [pf_{LS} - \frac{p}{r}f_{SS}\Psi'] & [pf_{LL} - (b + \frac{p}{r}f_S)\Psi'' - \frac{p}{r}f_{SL}\Psi'] & 0 \\ \frac{p}{r}f_{SS}g' & \left[(b + \frac{p}{r}f_S)\frac{g''}{g'}\Psi' + \frac{p}{r}f_{SL}g' \right] & 0 \end{bmatrix}}{|J|} < 0$$

since the sign of the numerator is negative:

$$\left(b + \frac{pf_S}{r}\right) \left[\underbrace{\frac{f_{SS}g'p\Psi''}{r}}_{(-)} - \underbrace{\frac{g''p\Psi'}{g'}}_{(-)} \underbrace{\left(\frac{\Psi'f_{SS}}{r} - f_{SL}\right)}_{(-)} \right] - \frac{g'p^2}{r} \underbrace{(f_{LL}f_{SS} - f_{SL}^2)}_{(+)} < 0$$

(26)

$$\frac{dS}{dp} = \frac{\begin{bmatrix} -f_F & pf_{FL} & [pf_{FF} - \Phi'] \\ \left[f_L + \frac{f_S}{r} \Psi' \right] & \left[pf_{LL} - \left(b + \frac{p}{r} f_S \right) \Psi'' - \frac{p}{r} f_{SL} \Psi' \right] & \left[pf_{LF} - \frac{p}{r} f_{SF} \Psi' \right] \\ -\frac{f_S}{r} g' & \left[\left(b + \frac{p}{r} f_S \right) \frac{g''}{g'} \Psi' + \frac{p}{r} f_{SL} g' \right] & \frac{p}{r} f_{SF} g' \end{bmatrix}}{|J|} \leq 0 \text{ or } \geq 0$$

since the sign of the numerator is indeterminate:

$$\begin{aligned} & \frac{p^2 g'}{r} \left[\frac{\Phi''}{p} \underbrace{(f_L f_{SL} - f_S f_{LL})}_{(+)} + f_S \underbrace{(f_{FF} f_{LL} - f_{FL}^2)}_{(+)} + f_L \underbrace{(f_{LF} f_{SF} - f_{FF} f_{SL})}_{(+)} + f_F \underbrace{(f_{LF} f_{SL} - f_{LL} f_{SF})}_{(+)} \right] + \\ & + \left(b + \frac{pf_S}{r} \right) \underbrace{\left(\frac{g'}{r} \Psi'' - \frac{g''}{r g'} (\Psi')^2 \right)}_{(+)} \underbrace{(pf_F f_{SF} - pf_S f_{FF} + f_S \Phi'')}_{(+)} + \\ & + \underbrace{\frac{g''}{g'} \Psi' \left(b + \frac{pf_S}{r} \right) (pf_F f_{LF} - pf_L f_{FF} + f_L \Phi'')}_{(-)} \leq 0 \text{ or } \geq 0 \end{aligned}$$

$$(27) \frac{dL_Q}{dp} = \frac{\begin{bmatrix} pf_{FS} & -f_F & [pf_{FF} - \Phi''] \\ \left[pf_{LS} - \frac{p}{r} f_{SS} \Psi' \right] & \left[f_L + \frac{f_S}{r} \Psi' \right] & \left[pf_{LF} - \frac{p}{r} f_{SF} \Psi' \right] \\ \frac{p}{r} f_{SS} g' & -\frac{f_S}{r} g' & \frac{p}{r} f_{SF} g' \end{bmatrix}}{|J|} > 0$$

since the sign of the numerator is positive:

$$\frac{p^2 g'}{r} \left[f_S \left(\underbrace{f_{LF} f_{SF} - f_{FF} f_{SL}}_{(+)} + \frac{\Phi''}{p} f_{SL} \right) + f_L \left(\underbrace{f_{FF} f_{SS} - f_{SF}^2}_{(+)} - \frac{\Phi''}{p} \underbrace{f_{SS}}_{(-)} \right) + f_F \underbrace{(f_{SF} f_{SL} - f_{LF} f_{SS})}_{(+)} \right] > 0$$

(28)

$$\frac{dF}{dp} = \frac{\begin{bmatrix} pf_{FS} & pf_{FL} & -f_F \\ \left[pf_{LS} - \frac{p}{r} f_{SS} \Psi' \right] & \left[pf_{LL} - \left(b + \frac{p}{r} f_S \right) \Psi'' - \frac{p}{r} f_{SL} \Psi' \right] & \left[f_L + \frac{f_S}{r} \Psi' \right] \\ \frac{p}{r} f_{SS} g' & \left[\left(b + \frac{p}{r} f_S \right) \frac{g''}{g'} \Psi' + \frac{p}{r} f_{SL} g' \right] & -\frac{f_S}{r} g' \end{bmatrix}}{|J|} \leq 0 \text{ or } \geq 0$$

since the sign of the numerator is indeterminate:

$$\begin{aligned} & \frac{pg'}{r} \left(b + \frac{pf_S}{r} \right) \underbrace{(f_F f_{SS} - f_S f_{SF})}_{(-)} \underbrace{\left(\frac{g''}{(g')^2} (\Psi')^2 - \Psi'' \right)}_{(-)} + \underbrace{\frac{pg''\Psi'}{g'}}_{(-)} \left(b + \frac{pf_S}{r} \right) \underbrace{(f_L f_{SF} - f_F f_{SL})}_{(?) } + \\ & + \frac{pg'}{r} \left[\underbrace{pf_S (f_{LF} f_{SL} - f_{LL} f_{SF})}_{(+)} + \underbrace{pf_L (f_{SF} f_{SL} - f_{LF} f_{SS})}_{(+)} + \underbrace{pf_F (f_{LL} f_{SS} - f_{SL}^2)}_{(+)} \right] \leq 0 \text{ or } \geq 0 \end{aligned}$$

$$\frac{dF}{dp} > 0 \text{ if } f_L f_{SF} - f_F f_{SL} \leq 0 \text{ or } \frac{\partial \left(\frac{f_F}{f_L} \right)}{\partial S} \leq 0, \text{ i.e. if an increase in soil capital increases}$$

marginal product of labour more than marginal product of fertilizer.

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List of variables

Q = Crop output

F = Fertilizer input

σ = Net soil loss

S = Soil capital

E = Downstream environmental quality

$b(\dot{S})$ = External flow benefit (or cost) of soil motion

v = Price of fertilizer

r = Interest rate

L_Q = Labour supply to agricultural production

L_C = Labour supply to soil conservation

w = Labour wage rate

$f(\cdot)$ = Agricultural production fcn.

p = Crop price

π = Agricultural profit

λ = Shadow value of soil

s = Subsidy to soil conservation

τ = Pollution charge

Determinants of Soil Capital³⁴

Anders Ekbom³⁵

Abstract

This paper combines knowledge from soil science and economics to estimate economic determinants of soil capital. Explaining soil capital facilitates a better understanding of constraints and opportunities for increased agricultural production and reduced land degradation. The study builds on an unusually rich data set that combines data on soil capital (represented by chemical and physical properties) and economic data on household characteristics, labour supply, crop allocation and conservation investments. The study yields both methodological and policy-relevant results.

On methodology, the analysis shows that soil capital is heterogeneous with soil properties widely distributed across the farms. Likewise, farmers' investment decisions and soil management vary widely across farms. Hence simplifications of soil capital, which are common in the economics literature, may have limited validity. On the other hand, soil science research limited to soils' biological, physical and chemical characteristics fail to recognize that soil is capital owned and managed by farmers. They thus run the risk of omitting important socio-economic determinants of soil capital. They also exclude the possibility to explain some of the dynamics that are determined by its stock character.

On policy, the study shows that farmers' soil conservation investments, allocation of labour, manure and fertilizer input, and crop choice indeed do determine variation in farmers' soil capital. Particularly strong positive effects on key soil nutrients (N,P,K) are observed for certain conservation technologies. Extension advice shows unexpectedly no significant effects on soil capital. The wide distribution of soil properties across farms reinforces the need to (i) tailor technical extension advice to the specific circumstances in each farm, and (ii) enhance the integration of farmers' knowledge and experiences, expert judgment and scientific soil analysis at the farm level.

Keywords: soil fertility, soil productivity, resource management;

JEL classification: Q12, Q20

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1. Introduction

Soil degradation and soil nutrient depletion are increasingly regarded as major constraints to food production in tropical environments of the world (Stoorvogel and Smaling, 1998; Pimentel and Kounang, 1998; Scherr, 1999). These problems are primarily caused by soil erosion, which is particularly damaging in the tropical highlands (Lal, 1987; 1995; Tengberg *et al*, 1998). The purpose of this paper is to estimate economic determinants of soil capital to facilitate a better understanding of the constraints and opportunities facing agricultural production and sustainable land use (Shiferaw and Holden, 1999, 2001; Nkonya *et al*, 2004).

In this paper we argue that research on soil issues has been carried out by two disciplines - soil science and economics – and that these are insufficiently integrated. Research in soil science has advanced our knowledge of the functions and complexities of soil e.g. how soil is formed and changes over time. The traditional focus has been on physical, chemical and biological determinants. The integration of economic theory or economic factors has been limited. Soil-related research in economics has focused *inter alia* on the impact of soil properties on agricultural production (see e.g. Berck and Helfand, 1990, Berck *et al*, 2000). Research on explaining soil as such has however been limited, despite the fact that soil is a key factor in the world's crop production. As showed by soil science, soil is not a constant or homogenous factor. It varies across time and spatially, and its properties are unevenly distributed down the soil profile, with profound implications for crop production (Paul and Clark, 1996; Sparks, 1999).

Although economic research on e.g. optimal soil use (see e.g. McConnell, 1983; Barrett, 1991, 1997; LaFrance, 1992) has developed our understanding of soil from an economics perspective, a large share of the economics research featuring soil has tended to ignore or over-simplify natural capital and soil in particular in the analysis (Barrett, 1991, Dasgupta and Mäler, 1997). In many models soil is presented as a homogeneous production factor represented by a single proxy such as land area, soil depth or some quality indicator. The important complexities explained by soil science are largely ignored. However, the different sets of knowledge accumulated in soil science and economics would benefit from enhanced integration. Specifically,

increasing the understanding of economic determinants to soil capital would thus fill a gap in the field. It may also contribute to enhanced policy making. In this paper we seek to combine knowledge from the two disciplines and study the relationship between soil capital and farm management.

Questions we address in this paper include: do production inputs like labour supply to cultivation, inorganic fertilizer and manure explain the status of various soil properties? Do age, gender and education of the household head contribute to explain the status of various soil properties? To what extent do soil conservation investments explain differences in various soil properties? What role does technical extension advisory services play in determining soil capital? What is the impact on soil capital of farmers' choice regarding land allocation to various crops?

The paper is organized as follows. Section 2 of the paper presents and discusses some of the relevant literature on soil research. Section 3 presents the model to be estimated. Section 4 presents the field study area, the data and data collection. Section 5 presents the statistical results and section 6 presents conclusions and some policy implications.

2. Research on Soil

In order to identify the economic determinants to soil capital, we need a profound understanding of what soil is. The research on soil in the natural sciences is vast. Research in soil sciences like pedology, edaphology, geomorphology, agronomy and ecology have developed our understanding of what soil is and how it is formed. Soil is usually represented by a (minimum) set of biological, physical and chemical properties. Typical properties include: *primary macro nutrients* such as nitrogen (N), phosphorus (P), potassium (K) and carbon (C), *secondary macro nutrients* such as calcium (Ca), magnesium (Mg) and sulphur, and *micro nutrients* such as iron (Fe), copper (Cu), *chemical properties* such as cation exchange capacity (CEC)³⁶,

³⁶ Cation exchange capacity (CEC) is the capacity of a soil for ion exchange of positively charged ions between the soil and the soil solution. CEC is an important soil property which is used as a measure of soil fertility and nutrient retention capacity. CEC is largest in clay soils.

alkalinity/acidity (pH) and structural properties³⁷ and texture³⁸. Jenny (1994) suggests that soil formation is a function of climate (*cl*), biota (*o*), topography (*r*), parent material (*p*), time (*t*) and other variables (*Z*): $S = f(cl, o, r, p, t, Z)$. Here, *S* is a vector of soil properties (or characteristics) and refers to the state of these properties at a point in time. Although the relationships between *cl*, *o*, *r*, *p* and *t* are generally supported (see e.g. Birkeland (1997); Bridges (1997); Gray and Murphy (2002)), the relative importance of these different factors is still debated (Gray and Humphreys, 2004).

Soil scientists have addressed the issue if and how the soils' complexities can be aggregated and properly represented in relation to its various functions.³⁹

Consequently, soil quality (SQ) has been developed as a concept to define soils' dynamic properties, grade and assess soils' agricultural potential, and to assess soils' ecosystem functions (Andrews et al, 2004). Soil quality has been defined as "capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" p.7 (Allan *et al.*, 1995). SQ is closely related to other concepts like soil fertility and soil productivity.⁴⁰ Identification and assessment of SQ are usually based on a minimum data set of biological, chemical and physical properties, which are transformed into a weighted Soil Quality Index (SQI)⁴¹. Given the choice of soil properties and weights, the intended soil use and its objective(s), specific SQIs can be identified for various soils. Although some argue for the potentials of this approach (see e.g. Karlen et al., 1997, 2003; Carter 2002),

³⁷ Soil structure is important since it determines the soil's porosity and air and water holding capacity.

³⁸ Texture represents grain size distribution of clay, silt and sand particles. It is an important factor for retention of water and nutrients, where clay has the highest capacity. However, clayish soils are more erodible. Good plant growth is usually favoured by more balanced soils e.g. sandy loams (Sparks, 1999).

³⁹ Production of food, fibre and fuel; filtering and buffering wastes and water, nutrient storage, provision of gene reserves and raw materials, cultural heritage and support for physical structures (Schjøning, 2004).

⁴⁰ *Soil productivity* has been defined as "the overall productive status of a soil arising from all aspects of its quality and status, such as its physical and structural condition as well as its chemical content". Similarly, *soil fertility* is defined as "the soil's ability to produce and reproduce. It is the aggregate status of a soil consequent on its physical, chemical and biological well-being" (Stocking and Murnaghan, 2001; p. 146). Other concepts include e.g. soil resilience, soil health, sustainable soil use, soil degradation including soil pollution (Coleman and Hendrix, 2004).

⁴¹ For instance, Tiwari *et al*, 2006 suggest that $SQI = \sum_{i=1}^n W_i Q(X_i)$ where W_i is the weight factor associated with each soil quality factor ($Q(X_i)$).

identification and use of SQ and SQIs have been criticized for being normative, use-dependent, biased towards crop production and certain geographical regions, and lack consideration of the fact that crops have different soil requirements; the unlimited diversity in farming strategies (e.g. choice of physical inputs, management and crops) implies an infinite number of unique SQ optima. The critiques argue that the complexities of soil can or should not be reduced to one technical denominator such as an index (Sojka and Upchurch, 1999, Sojka et al, 2003, Letey et al, 2003, Schjønning, 2004).

The soil sciences have developed our understanding of how soil is formed and how it changes as a result of natural phenomena. However, one perspective which is largely missing in the soil science literature is the contribution by economics: that soil is *capital* (McConnell, 1983, Barrett, 1997). All the observed soil properties can be – and are often shaped by the hand of the farmer. Hence, the farmer's characteristics, skills and choices may play a role for shaping the farmer's soil capital. For instance, Nkonya et al (2004) show that economic factors may contribute both positively and negatively to small-scale farmers' nutrient balances. They also show that the annual cost of nutrient mining (NPK-losses) among households subjected to erosion and other forms of soil degradation, amounts to around 20% of the farmers' income. By investing labour in soil conservation, farmers can increase their soil capital (build up soil productivity and soil fertility) and thus future harvests (Gachene and Kimaru, 2003). Soil erosion and failure to maintain soil fertility imply capital depreciation.

Economists argue for the importance of treating these soil conservation and erosion/nutrient depletion as dynamic processes in which a stock of *capital* is being built or depreciated (see e.g. Barbier, 1998). One of the fundamental insights from doing this is the long time lags and complicated dynamics involved from an investment in the past, to an improved (but not readily visible) stock in the present and to tangible increases in crop yields in the future.

Soil research in Kenya

Compared to many other developing countries, Kenya is relatively well endowed with soil-related research. Relevant studies focusing on the highlands include e.g. Ovuka

and Ekbohm (2001) who investigate the relationships between farmers' wealth levels (capital assets and income) and soil properties. Smaling *et al* (1993), Stoorvogel and Smaling (1998), van den Bosch *et al.* (1998), Hilhorst and Muchena (2000) and de Jager *et al.* (2001) identify soil nutrient balances of various farming systems. Ovuka (2000), Gachene (1995), Gachene *et al.* (1997) analyse the impact of soil change (erosion) on individual soil properties. Gachene *et al.* (1998) and Kilewe (1987) analyse the yield effects of soil erosion. Gicheru (1994) analyses effects of residue mulch and tillage on soil moisture. Batjes (2004) projects changes in carbon stocks in relation to land use. Hartemink *et al.* (2000) investigates the nitrogen dynamics in fallows and maize production for different soil types. Gicheru (1994) analyses the effects of mulch and tillage on soil moisture. Dunne (1979), Moore (1979) and Lewis (1985) estimate soil loss and sediment yields. Common to most of these and other similar studies in this research area is the fundamental lack of integration of soil data and economic variables in order to identify determinants of soil capital.

3. The Empirical Model

We assume that soil capital can be represented by a vector of individual soil properties,⁴² $\mathbf{S}=\{S_i\}$, $i=1..n$, and each soil property can be explained by a set of independent variables:

$$(1) \quad \mathbf{S} = f(\mathbf{H}, \mathbf{I}, X, \mathbf{PF}, \mathbf{R}).$$

In equation 1, \mathbf{H} represents a vector of household characteristics. \mathbf{I} is a vector of variables representing soil conservation investments: $\mathbf{I} \in \{I_1, I_2, I_3, \dots, I_{11}\}$. X represents technical extension advice provided to farmers on soil and water conservation. \mathbf{PF} is a vector of variables representing physical production factors used in the agriculture production. \mathbf{R} is a vector representing variables on crop allocation. These variables are explained in more detail in section 3 below.

⁴² It may be argued that soil capital would be better represented by some sort of index or a composite indicator. However, due to soils' inherent complexities and the arguments proposed by e.g. Sojka and Upchurch, 1999, Sojka *et al.*, 2003, Letey *et al.*, 2003 above, we use a disaggregated representation of soil.

The rationale for the specification of equation 1 is based on our hypothesis that Z contains a sub-set of economic factors, where $Z \in \{H, I, X, PF, R, E\}$, which may explain some of the variation in S . If we observe large variation in the distribution of soil properties across farms, and can assume that the basic (inherent) soil forming factors (climate, topography, bedrock etc.) proposed by Jenny (1994) are identical or at least very similar for all farms, then it is reasonable to assume that economic factors have roles to play in explaining farmers' variation in soil capital. Besides our proposition that soil is a heterogenous good, we also assume that farmers' decision on soil management and (re)investment is made up of a set of heterogenous decisions, which also vary across farms.

Ideally, identifying determinants of soil capital implies a study over a very long time horizon since several soil properties are shaped or accumulated over a long time. It is generally true that soil capital is relatively inert and constant, particularly in sub-soil layers (B- and C-horizon), partly because several natural soil-forming factors are relatively stable across time (Coleman and Hendrix, 2004). However, if the soil is subjected to e.g. erosion, drought and inadequate farming practices, the properties in the humus layer (O-horizon) and in the topsoil (A-horizon) can change very rapidly, with negative effects on fertility and productivity (Gachene, 1995; Tengberg *et al.*, 1998; Stoorvogel and Smaling, 1998). Hence, as an effect of soils' non-linear distribution of soil properties down the soil profile, even very deep soils (> 200cm) are at risk of quickly depreciating their economic value when subjected to erosion.

Since soil is capital, its development depends on the values of explanatory variables over a long time period. Consequently, the ideal data should cover the dependent and explanatory variables over many years, but such data are not available and we are thus forced to try to glean evidence from a cross-section of farms over a limited number of years. Based on equation 1 and our data (which covers between one and 4 years for different variables) we perform regression analysis in the hope that differences in behaviour between farms are reasonably stable so that the data we have is representative for a longer period of time. Some of our variables – such as the quality of soil conservation measures are themselves expert judgments of the accumulated effect of soil management over a fairly large number of years. In order to compare

regression coefficients, all variable values have been normalized around the statistical mean of the sample.

To prevent biased estimates caused by temporary events taking place during one growing season or a single year, our model includes field observations over eight consecutive growing seasons. Four year's data allow for impacts caused by inputs and measures implemented in the most recent time periods. It may be argued that inputs and investments undertaken longer back in time than four years might also have significant impacts on current soil properties. To some extent, the assessment of farmers' soil conservation structures is used to compensate for the lack of historical data. In practice, the observations of soil conservation investments (I_t-I_{t-1}) represent the physical outcome today of farmers' labour allocation to soil conservation in the past. Regarding annual inputs, it can be argued that the impact on current soil capital of historical inputs of fertilizer and manure diminishes rapidly as the nutrients are either taken up by plants, leached down the soil profile, volatilized or washed away (van den Bosch *et al*, 1998; Hilhorst and Muchena, 2000; Warren and Kihanda, 2001).

The proposition expressed by equation 1 warrants an explanation of how it should be understood. It does not represent a supply function of soil, nor does it represent a demand function for soil capital. Essentially, it describes an empirical metric for S . Primarily we are trying to answer the questions: what can be a reasonable representation of S and what determines S ? It is true that one can see equation 1 as a reduced form-expression of a system in which you would have both demand and supply. Defining whether equation 1 represents a demand *or* supply function of soil capital implies a non-separability problem since this is complex household production with unobservable, interacting characteristics, some of which evolving very slowly over time; then all we have is the reduced form - influenced by both demand and supply factors.

The econometric estimation of model 1 implies regression of multiple equations based on the same data. This implies that the error terms may be contemporaneously correlated across the equations. In order to address this potential problem we perform a joint estimation of the equations using Seemingly Unrelated Regression (SUR),

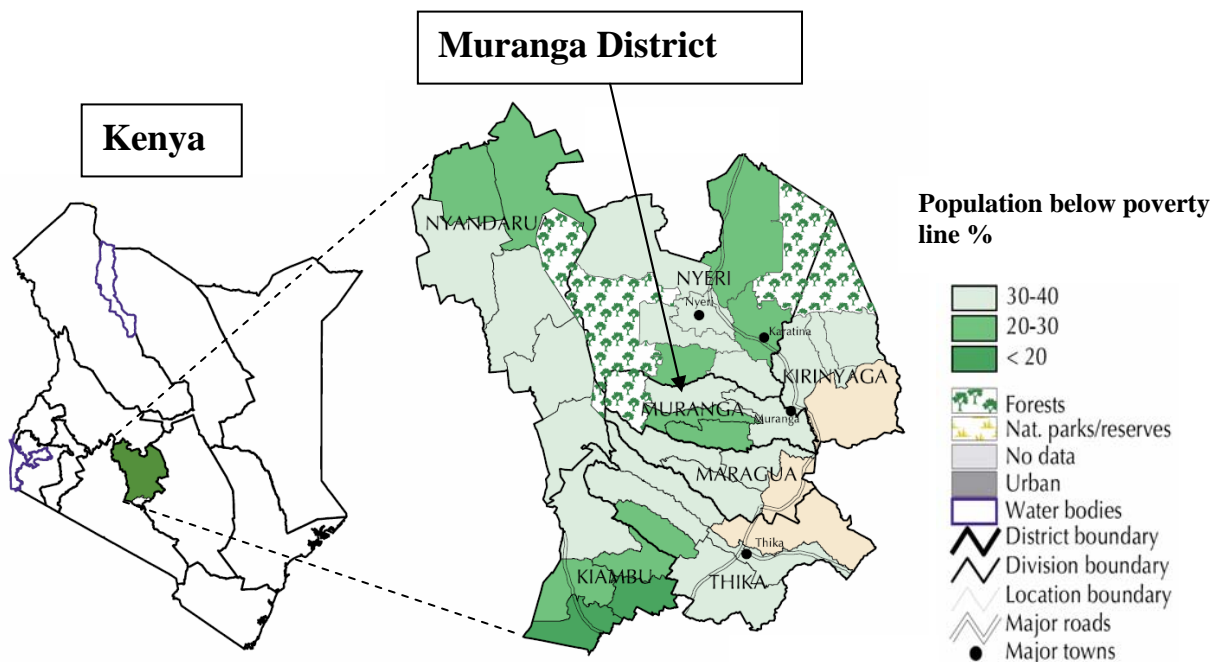
which is generally more efficient than separate estimation by Ordinary Least Squares (Zellner, 1962; Mehta and Swamy, 1976).

4. Field Study Area and Data

The Study Area

The study area is located in Muranga district, Kenya. It is located at 1500 m a.s.l. (0°43' S, 37°07' E) on the eastern slopes of Nyandarua range in Kenya's central highlands, south of Mount Kenya and south-east of the Aberdares forest reserve. It consists of two adjacent hydrologically defined catchments. Muranga district covers 2525 square kilometres and is part of the large drainage area of Kenya's central highlands. The climate is semi-humid (Sombroek *et al.*, 1980); average annual precipitation is 1,560 mm distributed over two rain seasons, March to May and October to December (Ovuka and Lindqvist, 2000). This facilitates two growing seasons each year.

Map 1. Kenya and the location of the study area



Source: World Resources Institute (2003)

The study area lies within the main coffee zone. The main soil type is humic nitisol, distributed over volcanic footridges. The soils are dark-reddish brown, well-drained and very deep (> 200 cm). Undisturbed, they are classified as fertile with very good yield potential (Jaetzold and Schmidt, 1983). However, erosion, strong leaching, continuous cropping and use of inorganic fertilizers, and other factors have severely reduced the soil fertility (Gachene and Kimaru, 2003).

Land tenure in the field study area has historically been relatively secure (Deweese, 1995). Traditionally it is based on family and clan affiliation and today, with some limitations⁴³, most of the farmers possess title deeds to surveyed, registered and adjudicated plots, which implies that tenure security is relatively high in a regional country comparison. The area shares many demographic, socio-economic and bio-physical features with the rest of the central highlands, which is home to the largest share of Kenya's population and food production. Hence the study of Muranga is of importance and relevance from a larger policy perspective. The agricultural lands in Muranga district are subject to large population pressure. This is manifested by high population density and increasing land fragmentation. At present, average farm size in the District is around 3.1 acres (or 1.2 hectares). The average farm size in our specific study site is only 2.4 acres. The population of the district is young, more than 60% of the population is constituted by children and teenagers. Given limited job opportunities besides agriculture, erosive rains, erodible soils and cultivation of steep slopes, the pressure on the district's soil capital is large and increasing. Identifying determinants of individual soil properties is therefore of considerable policy relevance.

Data and Data Collection

The data used in our analysis is obtained from a household survey conducted over a four-year's period (1995-98). The soil samples were collected and analysed in 1998. Based on a random sample, 252 small-scale farm households were identified and interviewed once every year between June and August.

⁴³ described in e.g. Kenya's draft Land policy; Ref.: Republic of Kenya, 2007. *National Land Policy* (draft), Ministry of Lands, National Land Policy Secretariat, <http://www.ardhi.go.ke/landpolicy.htm>

Dependent Variables: Collection and analysis of the soil samples followed the following standard procedure: composite soil samples were taken in all farms at 0-15 cm depth from the topsoil, based on three replicates in each farm field (*shamba*) along its slope (slope crest, mid slope, slope base). Places where mulch, manure and fertiliser were visible were avoided for soil sampling. The soil samples were air dried and analysed at the Department of Soil Science (DSS), University of Nairobi. The following soil properties were determined: grain size distribution (percentage sand-, silt- and clay-content), cation exchange capacity (CEC), rates of exchangeable potassium (K), sodium (Na), calcium (Ca), magnesium (Mg) and phosphorus (P) in the soil, organic carbon (C), total nitrogen (N) concentration, and the pH-level in water solution and in a calcium chloride (CaCl_2) solution.⁴⁴

The grain size distribution (texture) was determined by the hydrometer method. Grain size for sand, silt and clay is 0.05-2mm, 0.002-0.05mm and <0.002mm, respectively. CEC was analysed by leaching the soil with potassium ammonium acetate at pH 7. Na and K were determined using the flame photometer while Ca and Mg were determined using the atomic absorption spectrophotometer method. Available P was analysed using the Mehlich method, pH-level (H_2O) and pH-level (CaCl_2) were analysed using soil-water ratio and soil-salt ratio 1:2.5, respectively. Total N was identified using the Kjeldahl digestion method and organic C using Walkley and Black's method. Further details of the standard analytical methods used at the DSS can be found in Okalebo *et al.* (1993), Ekbom and Ovuka (2001) and Ovuka (2000).

Summary statistics of the soil sample properties (Table 1) show e.g. that the soils are clayish although the local variation is significant (between 16-82%). Moreover, the soils are acidic with a min-max $\text{pH}_{(\text{H}_2\text{O})}$ -level distribution between 4.1 and 8.2.

⁴⁴ The correlation coefficient between pH (H_2O) and pH (CaCl_2) is >0.95. Hence we have chosen to use pH (H_2O) to represent pH in our empirical analysis. Due to the non-linear nature of pH and the associated difficulties of interpreting regression coefficients, the data on pH has been converted by taking the absolute value of the difference between each farm's pH-value (pH_i) and neutrality ($|\text{pH}_i - 7|$).

Table 1. Summary Statistics of Soil Sample Properties

Soil Property	Unit	Mean ($\bar{\mu}$)	St. Dev. (σ)	Min.	Max.	$\lambda (= \sigma / \bar{\mu})$
pH _(H₂O)	-log H ⁺	5.63	0.66	4.1	8.2	0.12
pH _(CaCl)	-log H ⁺	4.72	0.62	3.1	7	0.13
Nitrogen (N)	%	0.18	0.05	0.08	0.32	0.28
Phosphorus (P)	ppm	17.90	24.60	1	195	1.37
Potassium (K)	m.eq./100 g.	2.36	1.72	0.15	11	0.73
Sodium (Na)	m.eq./100 g.	0.14	0.19	0.001	0.6	1.36
Calcium (Ca)	m.eq./100 g.	6.47	3.32	1.45	20	0.51
Magnesium (Mg)	m.eq./100 g.	5.28	2.83	0.02	17.42	0.54
Cation Exch. Capacity	m.eq./100 g.	15.80	5.45	7.2	36.8	0.35
Organic carbon (C)	g per kg	1.52	0.48	0.16	4.1	0.32
Sand	%	16.41	6.84	5	50	0.42
Silt	%	20.45	5.61	8	40	0.27
Clay	%	63.15	10.33	28	82	0.16

Fertility, proxied by the cation exchange capacity (CEC), is low⁴⁵. The summary statistics of the soil properties show two types of variation. First, there is large variation between farms. Second, there is large variation between the soil properties. This variation is captured by λ , which is the ratio between the standard deviation (σ) and the mean ($\bar{\mu}$) for each soil property. As indicated in table 1, λ ranges from 0.16 (clay content) to 1.37 (P).⁴⁶ Figures in Appendix 1 (A1-A7) show that the distribution of individual soil properties across farms is considerable. The figures illustrate that soil capital is not a fixed homogenous factor and that even within a very small geographical area (such as our study area) the variation between farms can be very large. This insight has important implications for farmers' management strategies as well as the government's provision of agricultural extension advice.

Independent Variables: The *household characteristics* (**H**) believed to explain soil capital include sex of household head (H_1), age of head (H_2), head's years of school education (H_3) and number of working adults in the household (H_4).

Soil conservation investments (**I**): The farmers in the area carry out a large number of physical as well as biological soil conservation measures. Formally, the data on the

⁴⁵ Soils with a CEC <16 m.eq./100g. soil are considered not to be fertile (Gachene and Kimaru, 2003).

⁴⁶ For acidity (pH) the variation coefficient is even lower but the comparison is not appropriate since this is a logarithmic index.

soil conservation technologies (I_i) is based on a quality index assigned to a set of individual technologies: $I \in \{I_1, I_2, \dots, I_{11}\}$. The index is derived from a practical expert assessment framework for evaluation of soil and water conservation investments (described in Thomas (1995) and Thomas et al. (1997)). Farm-specific ratings for individual soil conservation technologies are based on a rating scale ranging between 0 and 10. High rating implies that each soil conservation measure is characterized by high quality, based on the criteria presented below.

Physical conservation measures imply excavation of soil in various ways. Our data includes cut-off drains and terraces. The *cut-off drain* (COD) is a water retention ditch, with the purpose of infiltrating water into the soil in a controlled way. Position, length, depth and width of the drain are critical factors in determining the effectiveness to trap water (Thomas et al, 1997). Quality criteria for rating CODs also include: i) discharge, outlet and disposal of water; ii) vegetation cover and stability of the upper and lower embankment, (iii) and the amount of sediment and weeds inside the COD.

Terraces assessed in our sample include bench-terraces and built-up soil bunds. Coffee is mostly grown on bench terraces, which are usually covered by grass and forward-sloping or level along the contour. Built-up soil bunds are developed either by throwing soil up the slope (*fanya juu*), or down the slope (*fanya chini*). Commonly, grasses of various types are cultivated on top of the terrace embankment to provide livestock fodder, stabilize the terrace edges and reduce soil loss (Thomas et al, 1997). Eventually the soil bunds reduce the slope and develop into terraces. Criteria for quality rating include spacing, physical dimensions, location, stability and vegetative cover on the embankments. These factors are critical to prevent over-topping of water and breakage. High quality terraces are level along the contour, perpendicular to the natural slope, reduce the natural slope, and show no signs of breakage or surface run-off crossing the embankments. Poorly constructed or maintained structures are characterized by e.g. (signs of) soil erosion, surface-water run-off, breakage of embankments, poor vegetative cover along edges, and inadequate size and spacing⁴⁷ can easily break the structures and accelerate surface run-off and soil loss.

⁴⁷ >10m for steep slopes; >15m for moderate slopes; >20m for gentle slopes.

Biological conservation measures include conservation tillage, crop cover, integrated use of farm-yard manure for conservation purpose, mulching, green manure and agro-forestry. Fodder production and grazing areas can also be managed with soil conservation purposes. *Conservation tillage* implies seed-bed preparation, which facilitates adequate soil aeration, water absorption and retention, increased rooting depth and enhanced nutrient access, and establishment of ridges along the contour to prevent soil loss. *Fodder management* usually implies production of napier grass on terrace structures which together with stalks and stovers are supplied to livestock as feed. Management of grazing lands are assumed to be critical factors in determining soil capital. *Crop cover* pertains to the ground cover of the plants. Crop canopy and leaves reduce the velocity of raindrops and reduce splash erosion. Large crop cover is thus a critical factor for conserving the soil. Tree crops like coffee and tea have large ground cover, whereas onions, beans, potatoes and pulses generally have low ground cover. Criteria in the quality assessment also include e.g. area coverage of annual and perennial crops, inter-cropping, canopy cover, plant height and strength, and spacing between the plants.

Farm-yard manure is used to conserve or enhance the soil capital by mixing excrements from livestock and poultry with grasses and litter from agriculture. Criteria for good management implies quick incorporation of the manure into the soil (to avoid leaching and volatilization), and application which prevents physical loss of soil, and decline in soil fertility and moisture. *Mulching* implies application of dry, vegetative material in the field to cover the soil. It is stated to be an important factor to control erosion, reduce evaporation, improve soil structure, retain existing soil nutrients and soil moisture, and promote plants' uptake of additional nutrients from decomposed organic material (Ozara, 1992; Gachene and Kimaru, 2003). Factors determining quality of residue mulching include e.g. signs of (splash) erosion and pests, healthy crops, soil moisture and the distribution of the vegetative material.

Green manure is a form of fallowing and implies planting fast-growing cover crops (legumes, grasses) aiming at reducing soil erosion, maintaining soil moisture and improving soil fertility. Quality criteria include e.g. distribution and ground cover, soil

moisture and structure, heat protection, weed abundance, interference with main crops, and signs of pests associated with the green manure legume/grass.

Agro-forestry implies planting trees or perennial bushes in the farm field (Nair, 1997; Young, 1997). Agro-forestry is advocated to: (i) stabilize the soil and prevent mass-movements of soil such as landslides by the deep tree roots (Smith et al., 1999), (ii) retain soil moisture by providing shade from sunlight, (iii) reduce the velocity (erosivity) of rain due to the ground cover provided by the tree canopy and branches, (iv) enhance soil fertility by providing nutrients from decomposition of fallen leaves, and (v) increase yields from production of fruit crops, and provide timber, fodder and fuelwood. Crops from agro-forestry in the study area include coffee, mango, banana, avocado, lemon, papaya and macadamia nuts. Criteria for our quality assessment include e.g. choice, height, spacing, pruning and distribution of the trees, root exposure, ground cover, and signs of pests.

Although livestock numbers are decreasing in the central highlands, *fodder production* and *grazing land management* are important components of farmers' soil management systems. Quality criteria for fodder production include choice, area allocation, location and management of fodder crops (e.g. napier grass). Good managers produce fodder crops on terrace embankments, in contour strips (which develop into terraces), in valley bottoms, or in strategically placed blocks or rows. They practice "cut-and-carry" in a zero-grazing system, which re-cycles the nutrients and biomass back into the soil (van den Bosch *et al.*, 1998). Good management of grazing lands implies erosion control on pastures, appropriate supply of livestock in relation to pasture carrying capacity, rehabilitation of gullies, fencing or tethering, and grass planting on bare grounds. Low rating is given to denuded grazing land, which shows signs of erosion. Reseeding and gully reclamation are not practiced and the land is covered by woody bushes with a limited value from a soil fertility or productivity point of view.

Extension advice (X): The study area, like most agricultural areas in Kenya, has been subject to external soil conservation support over a number of years. Initially this was implemented by the British during the colonial rule. Since Independence in 1963, soil conservation has been advocated by the Government of Kenya (GoK). Due to the

coercive measures practiced by the British, soil conservation was resisted by the farmers during the first decade of independence. GoK's support took off in 1974 when a new public soil conservation project was launched. Progressively it has developed into a national program, and primarily built on individual farm visits provided by Ministry of Agriculture's local soil and water conservation experts. They are technical extension agents (TAs) providing on-site advice on soil and water conservation measures to individual households. Given the Program's goal to conserve soil, enhance soil fertility and boost food production, it is of interest to identify the impact of this service on individual soil properties. To facilitate analysis within our framework, X represents the total number of times each household has been visited over a four year's period by a technical extension agent and been provided advice on soil and water conservation.

Physical production factors (PF): Variables representing physical production factors used in the regression analysis include agricultural labour (L_0), fertilizer (F) and manure (M). All variables are expressed in terms of input per unit area (acre). The variables represent an aggregation of the annual input for each production factor over a four year's period. Hence, e.g. fertilizer is an un-weighted aggregation of fertilizer input over a four-year's period ($F = \sum_{t=1}^4 F_t$), which covers eight growing seasons.

Crop allocation (R): Crop allocation focuses on two crops: coffee (R_{coffee}) and maize (R_{maize}). They are expressed in terms of the area share allocated to them, respectively. Coffee and maize represent two key crops, where coffee is cultivated mainly for cash income and maize for food. Together, more than 75% of the farm area is allocated to coffee and maize. Remaining land is typically allocated to a small garden for cultivation of fruits and vegetables, homestead, livestock grazing (*boma*), other food and cash crops (beans, potatoes, bananas) and a small woodlot. Some farms are also occupied by wastelands (gullies, rocks). Arguably, each farmer pursues a certain farming strategy. Here, the choice and area allocation of crops in the farm constitute crucial decisions. Apparently, farms make very different choices. Arguably, this does not only impact on cash income and food supply, but also on soil capital. Specifically, allocating a relatively large (or small) land area to coffee and maize, respectively, will yield different outcomes regarding profitability, food security *and* soil properties.

The summary statistics (presented in table 2) indicate e.g. that as much as 30% of the households are reported to be headed by females. This group is represented by divorced women, widows and women with husbands who have migrated, at a more or less permanent basis, to nearby towns and the capital to seek an outcome. Most households are characterized by relatively old heads (mean>55 years), low formal education and few working adults. This is caused by large out-migration and puts a constraint on labour availability during the agricultural peak-season (seed-bed preparation and harvesting). Appropriate labour is also relatively scarce during the time for construction or maintenance of physical soil conservation structures.

Table 2. Summary Statistics of the Independent variables

Variable	Definition	Mean	Min.	Max.	Std Dev
H_1	Sex of Head (1=Male;0=Female)	0.71	0	1	0.45
H_2	Age of Head (years)	55.1	20	96	13.86
H_3	Education (years)	5.7	0	20	4.42
H_4	Working adults (nr)	2.5	1	7	1.10
I_1	Cut-off drains	5.13	0	10	2.70
I_2	Crop cover	5.56	0	10	2.05
I_3	Tillage practices	4.94	0	10	2.55
I_4	Manure conservation	5.26	0	10	2.53
I_5	Mulching	2.20	0	9	2.69
I_6	Green manure	0.77	0	8	1.90
I_7	Agro-forestry	3.88	0	10	2.68
I_8	Fodder management	5.44	0	10	2.27
I_9	Grazing land management	2.00	0	10	2.92
I_{10}	Terrace quality	5.79	0	10	2.02
I_{11}	Coffee trees (years)	22.41	0	54	11.61
X	TA-visits (nr.)	1.9	0	9	1.87
L_Q	Ag. Labour/acre (hrs)	3051	377	16224	1947.3
F	Fertilizer/acre (KSh)	5155	170	21320	3337.9
M	Manure/acre (KSh)	8001	0	54474	7319.4
R_{coffee}	Coffee area share (%)	34	0	80	17
R_{maize}	Maize area share (%)	42	0	100	20

When nothing else is stated the variables are indices based on expert judgement

According to the quality rating of soil conservation investments, the area as a whole acquires medium to low rates. Terraces rates highest (mean=5.8) followed by crop cover (5.6) and fodder management (5.4). The relatively low rating of the soil

conservation investments corroborates the substantial soil loss observed in the area⁴⁸. Moreover, the coffee trees in the study area are relatively old (>20 years), although variation in the sample is considerable.

On average, each household has been visited by a technical extension agent (TA) slightly less than two times during four years. Although this frequency seems little, each visit typically includes a thorough evaluation of existing land husbandry practices and practical advice on how to enhance soil conservation, soil fertility and crop productivity. It is thus difficult to say anything *a priori* on the effect of such a visit on the farmer's soil capital management. Given the government's comprehensive and long-standing financial extension support to farmers, it is of interest to assess the impact of the technical extension advice on their soil capital.

Due mainly to poverty, the level of commercial inputs is very low. Annual mean input of commercial fertilizer and farm-yard manure is approximately 3300 KSh per acre (≈ 50 US). The soil is only tilled with hand tools (hoe, machete). Draft animals are not used for ploughing. Instead, manual labour constitutes the largest production factor; the average farm supplies approximately 750 hours per acre per year.

Assuming that production factors have an impact on crop productivity *and* soil capital, it is of interest to investigate the predictive relationship between farmers' production factors and soil conservation quality, and individual soil properties.

⁴⁸ Although recent data is scarce, Lewis (1985) reports an average soil loss of 12 t/ha/yr in Muranga district. In some extreme cases it exceeds 150 t/ha/yr. Gachene (1995) and Gachene *et.al.* (1997) identify equally large soil losses in Kenya's Central Highlands and associated depreciation of key soil quality properties and yield losses. Dunne (1979) estimates that the Upper Tana river catchment in the Central Highlands, yields 4.8 million tons of soil sediment per year.

5. Statistical Results

Joint estimation of the multiple equations represented by model 1 above by Seemingly Unrelated Regression (Greene, 2000) yields the results presented in table 3-5 below.⁴⁹

Table 3. Regression results of primary macro nutrients

Indep. variable	Definition	Dependent Variables							
		Carbon		Nitrogen		Phosphorus		Potassium	
		Coeff.	t-value	Coeff.	t-value	Coeff.	t-value	Coeff.	t-value
α	Intercept	-0.517	-0.65	-1.893	-2.38	-0.429	-0.51	0.669	2.19
H_1	Sex of Head 1=M;0=F	0.134	2.80	0.028	0.60	0.040	0.83	0.002	0.11
H_2	Age of Head	0.148	0.27	0.391	0.69	-0.054	-0.09	0.340	1.60
H_3	Years of education	-0.284	-0.95	0.307	1.07	0.411	1.35	-0.232	-2.12
H_4	Nr of Working adults	0.088	0.74	-0.052	-0.46	-0.075	-0.62	0.081	1.81
I_1	Cut-off drains	0.112	1.18	-0.007	-0.07	-0.082	-0.84	0.164	4.48
I_2	Crop cover	0.123	1.76	0.129	1.92	0.028	0.39	0.223	7.31
I_3	Tillage practices	0.400	3.74	-0.036	-0.35	0.183	1.68	0.129	3.43
I_4	Manure conservation	0.263	2.06	0.441	3.61	0.570	4.37	0.185	4.01
I_5	Mulching	0.025	0.60	0.123	3.13	0.023	0.55	0.032	2.58
I_6	Green manure	0.144	2.12	-0.008	-0.12	-0.021	-0.30	0.061	2.72
I_7	Agro-forestry	-0.041	-0.61	0.310	4.85	-0.060	-0.87	-0.003	-0.21
I_8	Fodder management	0.060	0.58	-0.181	-1.86	-0.095	-0.91	0.003	0.12
I_9	Grazing land management	0.194	0.65	0.762	2.69	0.371	1.23	0.047	0.42
I_{10}	Terrace quality	0.095	0.99	0.355	3.86	-0.002	-0.02	-0.013	-0.42
I_{11}	Coffee trees (years)	0.093	1.59	0.180	3.22	0.063	1.06	0.046	2.16
X	TA-visits (nr.)	0.030	0.24	-0.175	-1.49	-0.149	-1.19	-0.033	-0.85
L_Q	Ag. Labour/acre (hrs)	-0.011	-0.10	0.145	1.49	0.118	1.14	-0.032	-1.11
F	Fertilizer/acre (KSh)	0.119	0.73	0.142	0.91	0.174	1.04	-0.032	-0.62
M	Manure/acre (KSh)	0.051	0.32	0.461	3.03	0.146	0.90	0.011	0.29
R_{coffee}	Coffee area share	-0.204	-1.94	-0.196	-1.96	0.003	0.03	0.035	0.99
R_{maize}	Maize area share	-0.124	-1.88	-0.102	-1.62	-0.026	-0.38	-0.013	-0.61

Interpretation of the statistical results

Carbon (C): In line with other research (see e.g. Smaling and Braun, 1996; Nandwa *et al.*, 2000; Batjes, 2004), soil conservation investments are generally positively associated with soil carbon. In particular, good ground cover from crops, conservation tillage, farm-yard manure and green manure significantly increase C concentrations in the soil stock. Similarly, cultivation of maize and coffee is associated with loss of soil

⁴⁹ General statistics obtained from SUR: System Weighted Mean Squared Error (MSE)=1.00, Degrees of Freedom=2465; System Weighted R-Square: 0.31.

organic C. Although the crop canopies provide some ground cover, relatively larger areas allocated to coffee and maize exposes the soil to erosion and loss of organic matter. The results suggest that selected erosion control measures and careful allocation of crops are effective means to build up organic matter, store carbon and prevent CO₂-emissions.

Nitrogen: Similar to carbon, investments in good soil conservation quality are associated with higher soil nitrogen content. This is particularly true for crop cover, integrated use of farm-yard manure for conservation purposes, mulching, agro-forestry, appropriate grazing land management and terraces, and older coffee trees. Plausible explanations to these results are that: good ground cover physically prevents loss on N from rain; application of chicken manure and cow-dung replenishes soil with nitrogen; mulching physically prevents loss of N from soil erosion and re-circulates N into the soil via decomposition of vegetative material (Hilhorst and Muchena, 2000; van den Bosch *et al.*, 1998; de Jager *et al.*, 2001). Although agro-forestry trees consume N for their growth, the results indicate a positive effect on soil nitrogen. There are many plausible explanations to this: the tree canopy prevents soil loss during the rain periods, deep roots capture leached nitrate from sub-soil layers and re-circulates N into the soil via decomposition of fallen leaves (Warren and Kihanda; 2001). The roots stabilize the soil and prevent erosion together with leaves, which physically protects the soil. The negative sign on fodder production is explained by the large loss of N associated with production of napier grass.⁵⁰

From a policy perspective it is of interest to note that the largest positive effects on soil N concentration are obtained from good grazing land management, integrated use of manure, well established terraces structures, and appropriate agro-forestry, in that order. Well maintained grazing areas consist of perennial grass cover, which effectively prevents soil loss (Thomas (1997; Stocking and Murnaghan, 2001). The positive impact of terraces is also well documented (see e.g. Gachene, 1995; Ovuka, 2000).

⁵⁰ Napier grass (*Pennisetum purpureum*) is the main fodder crop. It is grown to stabilize terrace embankments and harvested for milk and meat production. Van den Bosch *et al.* (1998) finds that napier production in a similar agricultural system in central Kenya reduces the soil N with 126 kg/ha per year.

The negative sign of coffee and maize area may be explained by the current farming practices associated with these crops. Despite some inflows of N from biological N-fixation, (in)organic fertilizers and atmospheric deposition, the reduction of soil nitrogen are considerable in a farming system like the one we study. To exemplify, production of coffee and maize under similar conditions in Kenya's highlands causes a net annual loss of N corresponding to 31 kg/ha and 88 kg/ha, respectively (van den Bosch *et al.*, 1998). De Jager *et al.* (2001) find that maize production under similar farming practices and agro-ecological conditions reduces soil N concentrations with 44 kg/ha per year.

The losses of N are mainly due to leaching, volatilization, erosion, crop harvesting and removal of crop residues. Due to the local soil type (*nitisol*) and inefficient fertilizer use, leaching of N to sub-soils is substantial (Warren and Kihanda, 2001). Loss of N in coffee production may also be a result of recent-years' abandonment of coffee trees. Low farm-gate coffee prices, high input prices and eroding coffee cooperative societies have worked in conjunction to reduce investments in the bench terraces on which coffee is grown and in the coffee trees (soil nutrient replenishment, pruning, weed control, pest management etc.). Consequently, younger trees in particular are developing poorly, and some have even been subject to uprooting. Older trees, however, show higher soil N concentrations. This might be explained by deeper roots (which can retrieve N from sub-soil layers), larger canopies (which prevents soil loss), more litter production (which supplies more N from the decomposed material), and better stabilization of the terrace structure than younger trees.

Phosphorus (P): Good tillage practices and manure conservation contribute positively to the soil's P content. As can be expected, re-circulating crop litter (stalks and stovers), cow dung and other types of farm-yard manure into the soil contributes to increase the soil's P concentration. The results are corroborated by e.g. de Jager *et al.* (2001) who find positive P nutrient balances for manure-based cultivation in a similar agro-ecological setting. Interestingly, application of chemical fertilizer during a four-year's period gives a positive but statistically insignificant effect on the soil's available P concentrations. This might be explained by losses from crop harvests and soil erosion, as well as quick fixation of inorganic phosphorus in acidic, strongly leached and eroded soils (Gachene and Kimaru, 2003). Application of farm-yard

manure (FYM) increases P availability in at least two important ways; first, manure itself contains significant amounts of phosphorus; second, fixation of P is inhibited since incorporation of FYM into the soil reduces soil acidity⁵¹.

Potassium (K): Several soil conservation technologies have a positive and significant relationship with soil K, particularly cut-off drains, good crop cover, conservation tillage, integrated use of (farm-yard and green) manure and mulching. This finding is no surprise since it has been found in several studies under similar conditions (Smaling *et al.*, 1993; Gachene *et al.*, 1997; Stoorvogel and Smaling, 1998, van den Bosch *et al.*, 1998; Hilhorst and Muchena, 2000). For instance, van den Bosch *et al.* (1998) find that 29% of K inflows to the soil originate from farm-yard manure and crop residues. These findings are of some interest in view of the fact that the farmers in the area typically use inorganic fertilizers with low or no potassium content. Although insufficient, the lack of inorganic K replenishment is to some extent compensated by the use of potassium promoting soil conservation measures and relatively large use of farm-yard manure for replenishment of K and other macro nutrients.

Generally, one would expect a positive and statistically significant effect of inorganic fertilizers on the soils' K concentration. However, volatilization, leaching, erosion and other nutrient depleting processes are strongly inhibiting factors to increasing the amount of K in the soil under the present farming system (van den Bosch *et al.*, 1998; Gachene and Kimaru, 2003).

⁵¹ Mean pH (H₂O) in FYM typically ranges between neutral to mildly alkaline (pH=7-7.8) in this farming system.

Table 4. Regressions results of pH, texture and cation exchange capacity

Indep. variable	Definition	Dependent Variables							
		pH		Clay		Silt		CEC	
		Coeff.	t-value	Coeff.	t-value	Coeff.	t-value	Coeff.	t-value
α	Intercept	-0.835	-0.87	1.320	5.74	1.430	1.67	-0.407	-1.00
H_1	Sex of Head 1=M;0=F	0.077	1.37	0.019	1.43	0.091	1.83	0.050	1.45
H_2	Age of Head	0.697	1.03	-0.261	-1.61	-0.911	-1.51	#	#
H_3	Years of education	-0.052	-0.15	0.174	2.10	-0.572	-1.86	0.274	1.26
H_4	Nr of Working adults	-0.105	-0.75	-0.043	-1.30	0.077	0.62	-0.009	-0.11
I_1	Cut-off drains	0.038	0.34	0.097	3.69	-0.034	-0.35	0.128	1.88
I_2	Crop cover	0.156	1.89	0.016	0.82	0.170	2.34	-0.004	-0.08
I_3	Tillage practices	-0.259	-2.08	0.048	1.62	0.088	0.80	0.194	2.51
I_4	Manure conservation	0.368	2.46	0.032	0.90	0.598	4.53	0.051	0.55
I_5	Mulching	0.183	3.81	-0.009	-0.75	0.110	2.59	-0.037	-1.26
I_6	Green manure	0.042	0.53	-0.050	-2.65	0.023	0.33	-0.010	-0.20
I_7	Agro-forestry	-0.066	-0.84	-0.004	-0.20	-0.029	-0.41	-0.011	-0.22
I_8	Fodder management	-0.338	-2.84	-0.006	-0.23	-0.088	-0.84	0.060	0.81
I_9	Grazing land management	0.860	2.48	0.037	0.45	0.131	0.43	0.329	1.53
I_{10}	Terrace quality	0.353	3.14	-0.044	-1.66	0.056	0.56	0.090	1.28
I_{11}	Coffee trees (years)	0.100	1.46	-0.033	-2.05	0.120	1.98	0.077	1.81
X	TA-visits (nr.)	-0.043	-0.30	-0.017	-0.50	-0.012	-0.09	0.018	0.20
L_Q	Ag. Labour/acre (hrs)	-0.127	-1.06	0.005	0.18	-0.052	-0.50	0.018	0.24
F	Fertilizer/acre (KSh)	0.061	0.32	0.166	3.66	-0.265	-1.57	0.167	1.44
M	Manure/acre (KSh)	0.074	0.40	0.026	0.59	0.032	0.20	0.126	1.10
R_{coffee}	Coffee area share	-0.068	-0.56	-0.290	-10.01	-0.049	-0.46	0.066	0.87
R_{maize}	Maize area share	-0.175	-2.27	-0.115	-6.30	-0.111	-1.63	-0.045	-0.96

- omitted

pH-level: Depending on which technology is used, soil conservation investments yield mixed results with respect to the pH-level. Good ground cover from the crops, manure conservation, mulching, good grazing land management and high-quality terraces are positively associated with the pH-level. Conversely, conservation tillage and fodder management yield negative signs. The net effect of soil conservation on pH thus seems to be an empirical issue. Irrespectively, the largest (positive) effects are given by manure conservation, management of grazing land and terraces. Increased area allocation to maize production is associated with lower pH. This result is important in view of the fact that the observed mean pH in the study area is rather low (mean=5.6) and that the optimal pH for production of many of the key crops produced in the area is typically higher (Thomas, 1997; Gachene and Kimaru, 2003). Since low pH (acidity) is a key constraint to increased production, the results call for selectivity in the choice of crops and conservation technologies.

Clay and silt: Soil conservation investments have mixed effects with respect the indicators of soil texture (clay, silt). The regression results show a positive relationship between cut-off drains and clay content. Silt is trapped by good crop cover, manure conservation, mulching and older coffee trees, which have bigger roots and larger canopies. Interestingly, green manure, terraces and coffee trees have small but negative effects on the soil's clay content. Determination of causes requires more study, but the effect of green manure may be explained by the fact that plowing of legumes into the soil exposes the soil to erosion risks, and loss of clay particles in particular. A similar effect of soil exposure may explain the strong negative relationship between area allocated to coffee and maize, respectively, and the soil's clay concentration. However, since crops have different requirements regarding texture (and other soil properties), it is difficult *a priori* to recommend one conservation technology before another.

Further, fertilizer input is positively associated with clay content. Although causality is not determined, it seems plausible to believe that clay facilitates (relatively higher) nutrient uptake since soils with relatively more clay content have higher nutrient-retention capacity than soils with coarser texture (Sparks, 1999).

Cation Exchange Capacity (CEC): The analysis of CEC shows that well established cut-off drains, good tillage practices and mature coffee trees are positively associated with CEC. This result is important because CEC is an important indicator of soil fertility (nutrient retention capacity), and leads us to conclude that investments in cut-off drains, appropriate conservation tillage and long-term maintenance of coffee trees (with deeper root system, larger canopy) build up soil capital and soil fertility.

Table 5. Regressions results of secondary macro nutrients

Indep. variable	Definition	Dependent Variables					
		Sodium		Calcium		Magnesium	
		Coeff.	t-value	Coeff.	t-value	Coeff.	t-value
α	Intercept	-0.055	-0.15	0.289	0.48	-0.027	-0.03
H_1	Sex of Head 1=M;0=F	-0.015	-0.71	0.019	0.55	-0.044	-0.85
H_2	Age of Head	-0.069	-0.27	0.122	0.29	0.493	0.78
H_3	Years of education	-0.031	-0.24	0.042	0.19	0.592	1.85
H_4	Nr of Working adults	0.023	0.44	0.021	0.24	-0.179	-1.40
I_1	Cut-off drains	0.074	1.80	0.094	1.38	0.132	1.29
I_2	Crop cover	0.004	0.15	-0.035	-0.70	0.248	3.29
I_3	Tillage practices	0.073	1.58	0.032	0.41	0.281	2.45
I_4	Manure conservation	-0.059	-1.08	-0.034	-0.37	-0.002	-0.01
I_5	Mulching	0.020	1.13	0.039	1.31	0.103	2.33
I_6	Green manure	-0.015	-0.51	-0.058	-1.20	-0.085	-1.17
I_7	Agro-forestry	0.034	1.20	0.015	0.31	0.065	0.91
I_8	Fodder management	-0.007	-0.15	-0.032	-0.44	0.042	0.38
I_9	Grazing land management	0.718	5.62	0.258	1.21	-0.239	-0.75
I_{10}	Terrace quality	0.053	1.28	0.042	0.60	-0.092	-0.89
I_{11}	Coffee trees (years)	0.036	1.43	0.170	4.03	-0.037	-0.59
X	TA-visits (nr.)	-0.046	-0.86	0.063	0.72	-0.140	-1.06
L_Q	Ag. Labour/acre (hrs)	0.065	1.48	-0.050	-0.69	-0.039	-0.36
F	Fertilizer/acre (KSh)	0.344	4.89	0.084	0.72	0.045	0.26
M	Manure/acre (KSh)	0.057	0.84	0.017	0.15	0.103	0.61
R_{coffee}	Coffee area share	-0.093	-2.07	-0.032	-0.43	0.024	0.21
R_{maize}	Maize area share	-0.123	-4.32	-0.069	-1.46	-0.058	-0.82

Secondary macro-nutrients: The regression results indicate that all statistically significant effects of soil conservation investments are positively associated with Na, Ca, and Mg. The specific conservation technologies with positive effects include high-quality cut-off drains, crop cover, conservation tillage, mulching and grazing land management. Older coffee trees are also positively correlated with soil Ca. This finding is arguably explained by the same factors (deeper roots, litter, larger canopy etc.), which cause a positive relationship between mature coffee trees and C, N, P and K, respectively. Significant positive effects on Na are also observed for agricultural labour and inorganic fertilizer, whereas negative signs are observed between Na and coffee and maize cultivation, respectively. This is probably explained by the current farming practices, where coffee and maize are cultivated with limited soil nutrient replenishment via e.g. fallows or (in)organic fertilizers. Loss of micro-nutrients due to insufficient soil conservation and continuous cultivation is in accord with other

studies (e.g. Gachene, 1995; Gachene *et al.*, 1997; Ovuka, 2000) under similar conditions.

6. Conclusions and Policy Implications

Our study has both methodological and policy implications. For soil capital to be a relevant variable in economic analysis, we have to account for the fact that it is heterogenous and consists of several properties, which change over time and are unevenly distributed across farms and down the soil profile (Warren and Kihanda, 2001). The diversity of S in reality implies e.g. that economic analyses of agricultural production in developing countries ought to pay more attention to the levels and relative proportions of key soil properties, their relationship with crops' diverse requirements for optimal growth, *and* the roles played traditional economic production factors such as labour input. Hence, economic abstractions of S such as soil depth need qualification since shallow soils may be fertile while deep soils may be quite infertile if eroded, leached or subjected to other forms of degradation. Ideally, economic analyses, which include soil capital, should strive for more diversity and complexity in the way soil is represented.

In agronomic research it is important to acknowledge soil as a form of capital. From this follows that soil, however important, is one asset among others in a farmer's portfolio. Soil capital depreciation may be an individually rational strategy if, for instance, reinvestment is too costly (van der Pol and Traore, 1993; Nkonya *et al.*, 2004), or if the soil capital is substituted for other capital which is more productive or yields a higher interest rate. As indicated by the wide distribution of S_i across farms, soil capital is shaped (accumulated, depreciated) by the farmer and not only the outcome of bio-physical factors such as climate, geology and topography. Farmers' characteristics and management strategies are heterogenous across farms and have pervasive impacts not only on crop yield (the resource rent) but also on the formation of the capital stock over time. Failure to acknowledge the differing roles and preferences of the farmer and his/her incentives, choices, constraints and characteristics, introduces the risk of omitting crucial variables in the analysis of soil productivity and soil change.

Interesting findings from the estimation results include:

- (i) *the (generally) positive effects of soil conservation investments on soil properties*; farmers who have made considerable efforts over time to establish and maintain high-quality conservation structures have been rewarded by higher macro-nutrient levels; It is however, also noticeable that some conservation investments show no significant effects on certain soil properties. Careful selection of conservation technology is hence of great importance in the efforts to sustain soil capital. Moreover, there is no clear pattern indicating that physical/structural conservation measures dominate biological conservation measures, or vice versa, regarding their respective impact on soil properties.
- (ii) *the negative effect of coffee and maize production on soil nutrients (C, N, Na), clay concentration and pH (maize)*. Given the farmers' large land allocation to maize and coffee production (>75%), it should be of policy interest to review the incentives for crop choice and the potential soil impacts of promoting other, more nutrient-efficient crop mixes. This is particularly important in view of the facts that crop choice matters a lot for soil structure, soil nutrient balance (coffee and maize production yields negative nutrient balances), and that some crops "mine" nutrients considerably more than others (van den Bosch *et al.*, 1998; de Jager *et al.*, 2001).
- (iii) *Visual field assessment and laboratory soil sample analysis are useful complements*. The results show that visual field assessment of soil conservation technologies can give a good indication of farmers' general soil quality. However, to ensure adequate knowledge on the links between conservation status and soil status it is necessary to increase their specific knowledge on individual soil properties. Hence, for farmers to optimize their production visual field assessment based on expert judgement ought to be complemented with (more frequent use of) laboratory-based soil sample analysis.

Our results also have some important broader policy implications. The diversity in farmers' soil capital, production strategies and general farming systems (including conservation investments) point at the importance of internalizing these aspects in the formulation the government's policies and extension advice on sustainable agriculture. Our findings reinforce the importance of providing extension advice and

general farmer support, which is based on farmers' experiences and preferences, expert judgment *as well as* site-specific information based on and scientific analysis (e.g. soil sample analysis). Such an approach would integrate farmers' knowledge and practices, extension services and research to a larger extent than at present, and promote increased agricultural productivity *and* sustained soil capital.

Appendix 1: Distribution of Soil Properties

Figure A1. Distribution of pH (H₂O) and pH (CaCl)

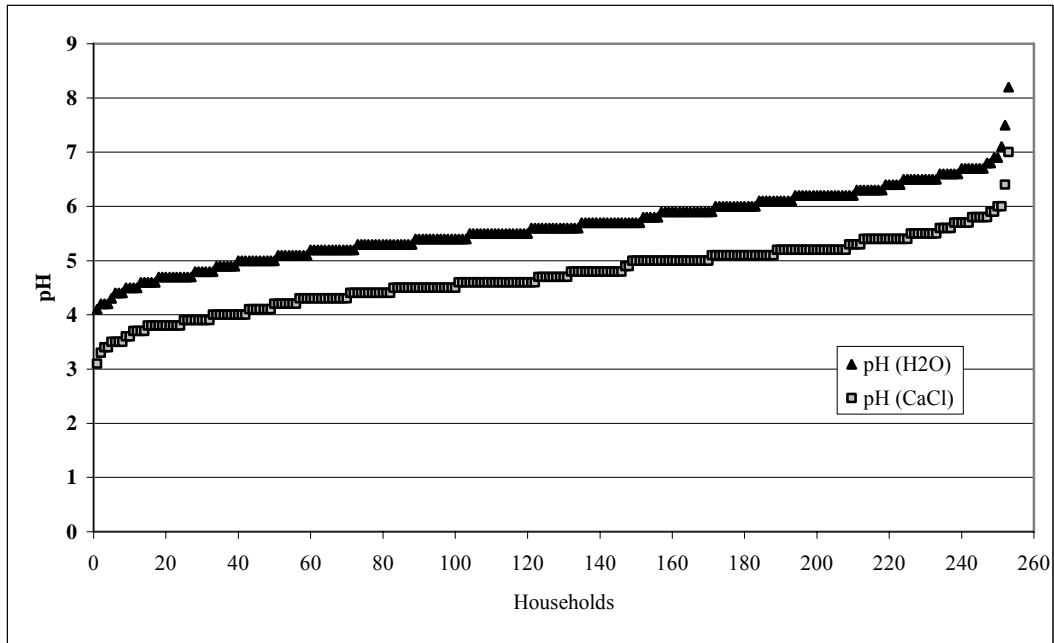


Figure A2. Distribution of Carbon (C) (%)

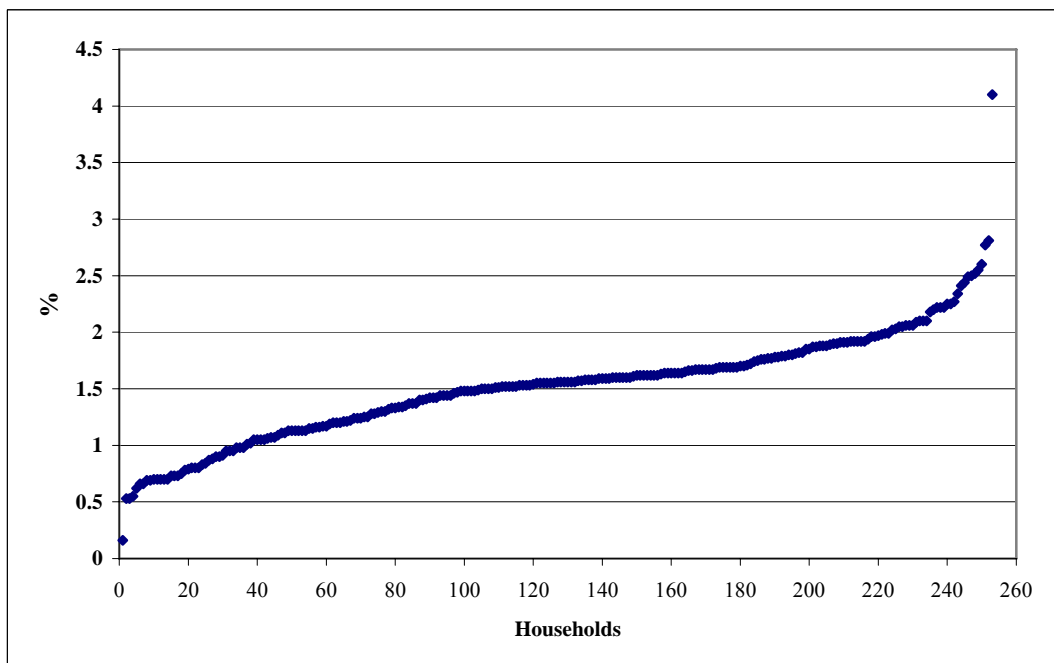


Figure A3. Distribution of Nitrogen (N) (m.eq./100 g.)

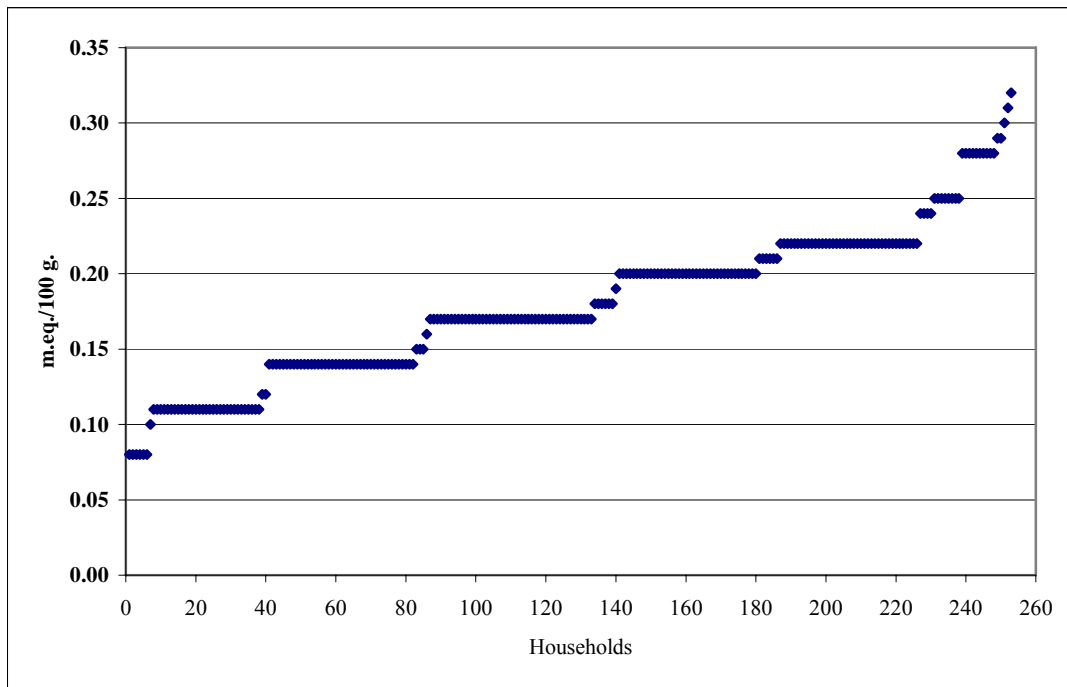


Figure A4. Distribution of Phosphorus (P) (ppm)

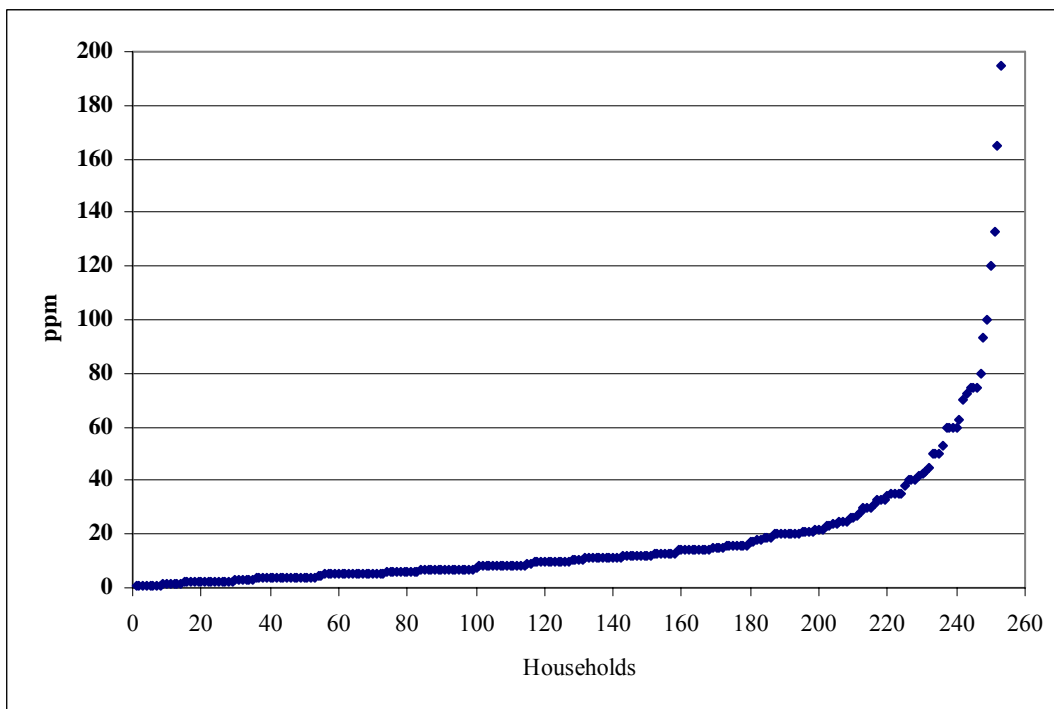


Figure A5. Distribution of Potassium (K), Calcium (Ca), Magnesium (Mg) and Cation Exchange Capacity (CEC) (m.eq./100 g.)

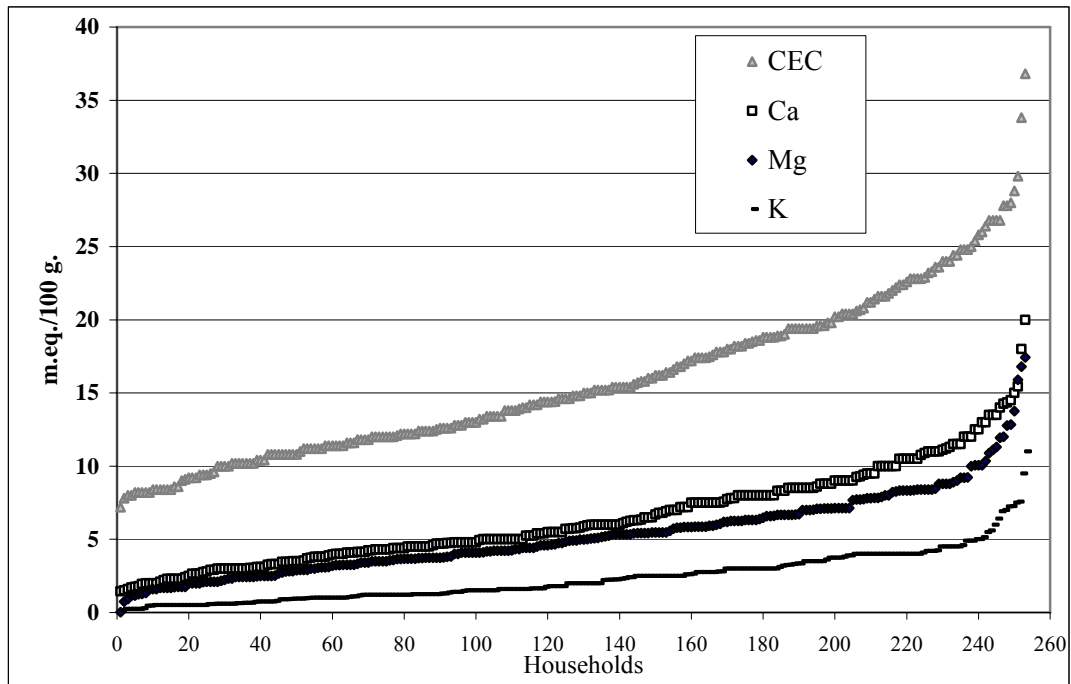


Figure A6. Distribution of Sodium (Na) (m.eq./100 g.)

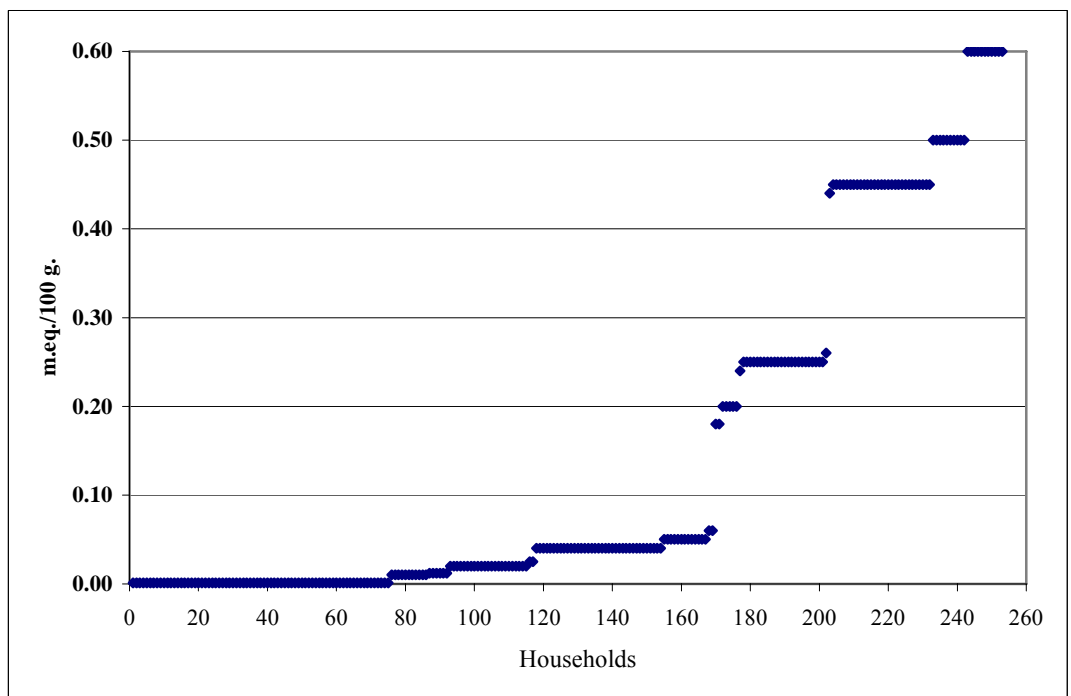
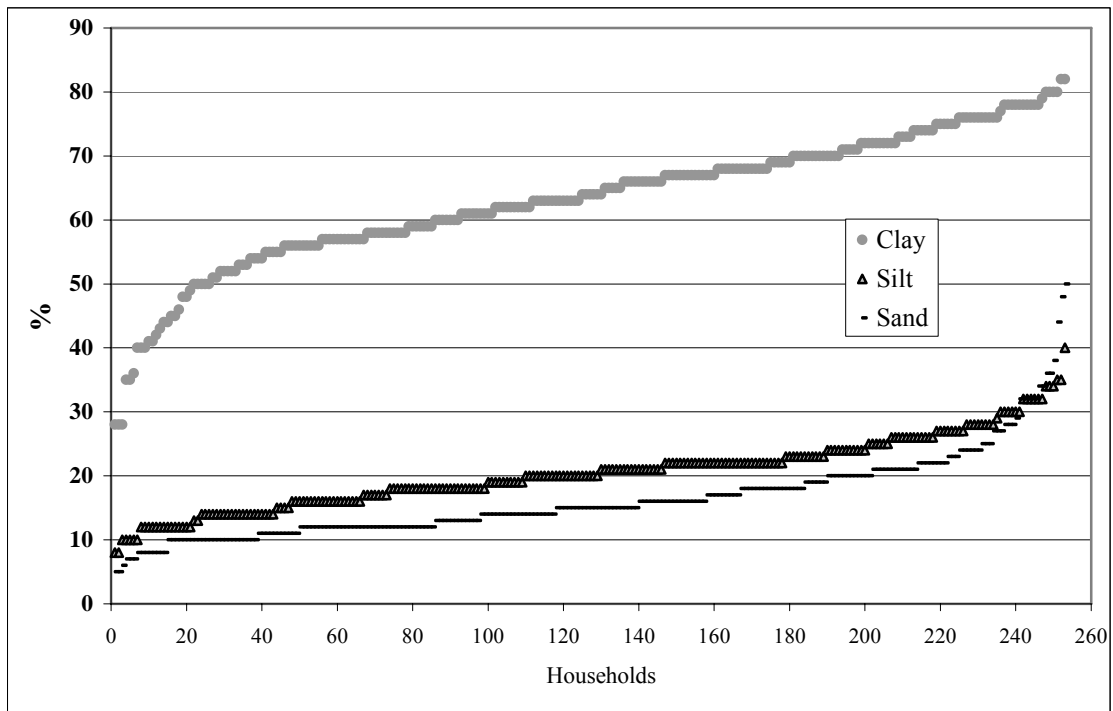


Figure A7. Distribution of Sand, Silt and Clay (%)



Appendix 2a. Correlation Coefficients of Soil Properties

	pH ^a	pH ^b	C	N	K	Na	Ca	Mg	CEC	P	Sand	Silt	Clay
pH^a	1	0.95	-0.02	0.10	0.08	-0.20	0.53	0.57	0.59	0.36	-0.06	0.17	-0.05
		<i><.0001</i>	<i>0.717</i>	<i>0.108</i>	<i>0.200</i>	<i>0.001</i>	<i><.0001</i>	<i><.0001</i>	<i><.0001</i>	<i><.0001</i>	<i>0.38</i>	<i>0.01</i>	<i>0.40</i>
pH^b		1	-0.07	0.10	0.06	-0.22	0.49	0.56	0.56	0.36	-0.10	0.12	0.00
			<i>0.250</i>	<i>0.131</i>	<i>0.365</i>	<i>0.001</i>	<i><.0001</i>	<i><.0001</i>	<i><.0001</i>	<i><.0001</i>	<i>0.12</i>	<i>0.07</i>	<i>0.98</i>
Carbon (C)			1	0.65	0.11	-0.01	-0.06	-0.17	-0.05	0.05	0.17	0.27	-0.26
				<i><.0001</i>	<i>0.09</i>	<i>0.87</i>	<i>0.37</i>	<i>0.01</i>	<i>0.40</i>	<i>0.40</i>	<i>0.01</i>	<i><.0001</i>	<i><.0001</i>
Nitrogen (N)				1	0.10	-0.11	-0.01	-0.02	0.06	0.06	0.04	0.19	-0.13
					<i>0.12</i>	<i>0.09</i>	<i>0.91</i>	<i>0.71</i>	<i>0.31</i>	<i>0.35</i>	<i>0.56</i>	<i>0.00</i>	<i>0.04</i>
Potassium (K)					1	0.23	-0.02	-0.04	0.26	0.10	0.13	0.12	-0.15
						<i>0.00</i>	<i>0.75</i>	<i>0.54</i>	<i><.0001</i>	<i>0.10</i>	<i>0.05</i>	<i>0.06</i>	<i>0.02</i>
Sodium (Na)						1	-0.14	-0.17	-0.10	-0.10	0.14	0.05	-0.12
							<i>0.03</i>	<i>0.01</i>	<i>0.10</i>	<i>0.10</i>	<i>0.02</i>	<i>0.44</i>	<i>0.05</i>
Calcium (Ca)							1	0.74	0.79	0.35	0.00	0.24	-0.13
								<i><.0001</i>	<i><.0001</i>	<i><.0001</i>	<i>0.99</i>	<i>0.00</i>	<i>0.04</i>
Magnesium (Mg)								1	0.84	0.26	-0.07	0.22	-0.08
									<i><.0001</i>	<i><.0001</i>	<i>0.28</i>	<i>0.00</i>	<i>0.22</i>
Cation Exchange Capacity (CEC)									1	0.36	-0.01	0.27	-0.14
										<i><.0001</i>	<i>0.89</i>	<i><.0001</i>	<i>0.02</i>
Phosphorus (P)										1	0.07	0.10	-0.10
											<i>0.27</i>	<i>0.11</i>	<i>0.11</i>
Sand content											1	0.37	-0.86
												<i><.0001</i>	<i><.0001</i>
Silt content												1	-0.79
													<i><.0001</i>
Clay content													1

^a measured in H₂O-solution

^b measured in CaCl-solution

Appendix 3. Cross Model Covariance and Correlation

Cross Model Covariance												
Variable	S _i	pH	C	N	K	Na	Ca	Mg	CEC	P	Silt	Clay
S ₁	pH	1.20	0.29	0.10	0.16	0.01	0.02	0.25	0.15	0.14	-0.04	0.56
S ₂	C		0.88	0.02	0.10	0.02	0.02	0.02	0.25	0.08	0.02	0.24
S ₃	N			0.80	0.05	0.02	-0.01	0.13	0.03	0.25	0.06	0.10
S ₄	K				0.27	0.03	0.02	0.04	0.09	0.03	0.01	0.15
S ₅	Na					0.16	-0.01	0.05	0.01	0.03	0.00	0.01
S ₆	Ca						0.45	0.01	0.07	0.08	0.02	0.03
S ₇	Mg							1.01	0.08	0.24	0.00	0.10
S ₈	CEC								0.46	0.09	0.03	0.09
S ₉	P									0.91	0.03	0.04
S ₁₀	Silt										0.07	-0.02
S ₁₁	Clay											0.93

Cross Model Correlation												
Variable	S _i	pH	C	N	K	Na	Ca	Mg	CEC	P	Silt	Clay
S ₁	pH	1.00	0.28	0.10	0.28	0.01	0.03	0.23	0.20	0.13	-0.14	0.53
S ₂	C		1.00	0.03	0.20	0.04	0.03	0.02	0.39	0.09	0.09	0.26
S ₃	N			1.00	0.11	0.05	-0.01	0.14	0.05	0.29	0.26	0.12
S ₄	K				1.00	0.15	0.06	0.08	0.26	0.06	0.09	0.29
S ₅	Na					1.00	-0.04	0.12	0.04	0.07	-0.02	0.01
S ₆	Ca						1.00	0.02	0.16	0.12	0.10	0.05
S ₇	Mg							1.00	0.12	0.25	0.00	0.11
S ₈	CEC								1.00	0.15	0.15	0.14
S ₉	P									1.00	0.13	0.04
S ₁₀	Silt										1.00	-0.07
S ₁₁	Clay											1.00

Appendix 5. Cross Model Inverse Correlation and Covariance

		Cross Model Inverse Correlation										
Variable	S _i	pH	C	N	K	Na	Ca	Mg	CEC	P	Silt	Clay
S ₁	pH	1.59	-0.21	-0.06	-0.18	0.07	0.02	-0.23	-0.08	-0.10	0.25	-0.67
S ₂	C		1.30	0.07	-0.03	-0.04	0.07	0.10	-0.44	-0.05	-0.12	-0.19
S ₃	N			1.20	-0.05	-0.03	0.09	-0.07	0.04	-0.29	-0.31	-0.12
S ₄	K				1.21	-0.17	-0.02	0.02	-0.22	0.03	-0.10	-0.22
S ₅	Na					1.05	0.05	-0.11	0.01	-0.05	0.06	0.03
S ₆	Ca						1.06	0.02	-0.16	-0.13	-0.10	-0.07
S ₇	Mg							1.14	-0.10	-0.23	0.02	0.00
S ₈	CEC								1.30	-0.08	-0.12	0.05
S ₉	P									1.19	-0.06	0.08
S ₁₀	Silt										1.18	0.07
S ₁₁	Clay											1.48

		Cross Model Inverse Covariance										
Variable	S _i	pH	C	N	K	Na	Ca	Mg	CEC	P	Silt	Clay
S ₁	pH	1.32	-0.21	-0.06	-0.32	0.16	0.02	-0.21	-0.11	-0.10	0.87	-0.63
S ₂	C		1.48	0.08	-0.06	-0.10	0.11	0.11	-0.69	-0.06	-0.48	-0.21
S ₃	N			1.50	-0.12	-0.07	0.14	-0.08	0.07	-0.34	-1.34	-0.14
S ₄	K				4.51	-0.81	-0.07	0.04	-0.61	0.07	-0.75	-0.44
S ₅	Na					6.45	0.18	-0.28	0.04	-0.12	0.53	0.07
S ₆	Ca						2.33	0.03	-0.34	-0.21	-0.55	-0.10
S ₇	Mg							1.13	-0.15	-0.24	0.07	0.00
S ₈	CEC								2.83	-0.13	-0.70	0.07
S ₉	P									1.31	-0.25	0.09
S ₁₀	Silt										17.47	0.26
S ₁₁	Clay											1.59

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Soil Properties and Soil Conservation Investments in Agricultural Production - a Case study of Kenya's Central Highlands⁵²

Anders Ekbom⁵³

Abstract

This paper integrates traditional economic variables, soil properties and variables on soil conservation technologies in order to estimate agricultural output among small-scale farmers in Kenya's central highlands. The study has methodological, empirical as well as policy results.

The key methodological result is that integrating traditional economics and soil science is highly worthwhile in this area of research. Omitting measures of soil capital can cause omitted variables bias since farmers' choice of inputs depend both on the quality and status of the soil capital and on other economic conditions such as availability and cost of labour, fertilizers, manure and other inputs.

The study shows that: (i) models which include soil capital and soil conservation technologies yield a considerably lower output elasticity of farm-yard manure; (ii) mean output elasticities of key soil nutrients like nitrogen (N) and potassium (K) are positive and relatively large; (iii) counter to our expectations, the mean output elasticity of phosphorus (P) is negative; (iv) soil conservation technologies like green manure and terraces are positively associated with output and yield relatively large output elasticities.

The central policy conclusion is that while fertilizers are generally beneficial, their application is a complex art and more is not necessarily better. The limited local market supply of fertilizers, combined with the different output effects of N, P and K, point at the importance of improving the performance of input markets and strengthening agricultural extension. Further, given the policy debate on the impact and usefulness of government subsidies to soil conservation, our results suggest that soil conservation investments contribute to increase farmers' output. Consequently, government support to appropriate soil conservation investments arrests soil erosion, prevents downstream externalities and assists farmers' efforts to increase food production and food security.

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1. Introduction

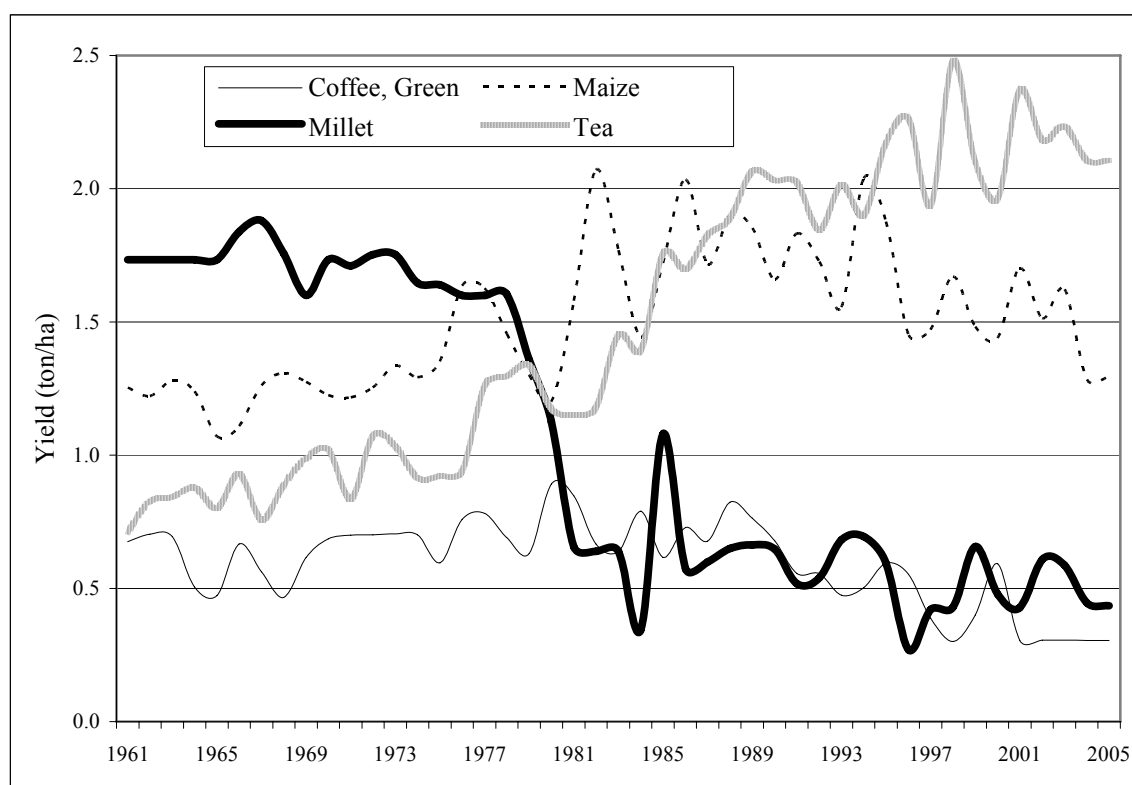
The purpose of this paper is to increase our understanding of the determinants of agricultural production by integrating models and methods from economics and soil science. The rationale for this paper is the opportunity to synthesise two areas of analysis: economic studies typically do not include soil variables; soil studies typically focus exclusively on soil properties and other bio-physical variables. The vast majority of economic studies fitting agricultural production functions to empirical data focuses on variables such as labour, capital, technology and inputs like chemical fertilizers, farm-yard manure and pesticides (see e.g. Deolalikar and Vijverberg, 1987; Widawsky *et al.*, 1998; Carrasco-Tauber and Moffitt, 1992; Fulginiti and Perrin, 1998; Gerdin 2002). Certainly, there are exceptions to these generalizations, for instance Sherlund *et al.* (2002), who also includes a set of environmental variables; Nkonya *et al.* (2004) use data from Uganda to identify determinants of soil nutrient balances in small-scale crop production; Mundlak *et al.* (1997) estimate the role of potential dry matter and water availability for crop production in a cross-country analysis.

Agronomic or soil-scientific studies have contributed to our understanding of the bio-physical factors in agricultural production (see e.g. Rutunga *et al.*, 1998; Hartemink *et al.*, 2000; Mureithi *et al.*, 2003). However, these types of studies typically do not explain the role of economic factors. The analyses are usually done in repeated field trials on controlled plots at research stations, and exclude capital, labour and other vital production factors. Consequently, key issues like labour productivity are rarely estimated (Smaling *et al.*, 1993; Hartemink *et al.*, 2000). More importantly, omission of labour and agricultural capital will bias all other results, and ultimately the problem is that controlled field experiments have little similarity to real agriculture. To exemplify, omission of labour in controlled experiments of “optimal application” of fertilizer neglects the trade off or substitution between labour (for soil amelioration) and fertilizer. The (implicit) price of agricultural labour partly determines the supply of fertilizer. This applies to several inputs for which labour functions as a substitute or a complement.

Crop Production in Kenya

Understanding the determinants to crop production is particularly important in Kenya. Poverty in Kenya is widespread and agricultural development has been modest in view of the population growth, the food needs and the progress made in other regions of the world. As indicated in figure 1 below, productivity for key crops like coffee and millet has decreased over time, and maize productivity has increased only marginally. Although production of tea and some other crops has increased over time, the average population growth of 3.2 % 1961-2005 and poor performance in the agricultural sector have actually *reduced* food production per capita over this period.

Figure 1. Agricultural Productivity (ton/ha) in Kenya 1961-2005 (selected crops)



Source: FAO database on agriculture (<http://faostat.fao.org/>)

Many economic studies have attempted to explain Kenya's agricultural performance (see e.g. Gerdin, 2002), but they typically have little or no information on soil capital and soil change, despite the fact that soil is a key capital asset in agricultural production, and that soil erosion significantly depreciates soil capital, reduces crop yields, and cause large costs to society. As an indication, costs of soil erosion in

Kenya may translate into losses of 3.8% of GDP. This cost equals Kenya's total annual electricity production or agricultural exports (Cohen *et al.*, 2006). Hidden costs of this magnitude and the lack of integration between traditional economic factors, soil conservation investments and soil properties motivate this particular study.

The paper is organized as follows. Section 2 presents the field study area. Section 3 presents the production function model and the key equations to be empirically estimated. Section 4 presents the data. Section 5 presents the statistical results and section 6 concludes the paper by presenting a summary and some policy conclusions.

4. The Study Area

The study area is located in Muranga district, which is part of the high-potential (fertile) agricultural areas in Kenya's highlands. It is located at around 1500 m a.s.l. (0°43' S, 37°07' E) south of Mount Kenya and south-east of the Aberdares forest reserve, which form a large drainage area to the Indian Ocean. It has two rainy seasons with mean annual precipitation of 1560 mm (Ovuka and Lindqvist, 2000) and shares many demographic, socio-economic and bio-physical features with other districts located in the Central Highlands. Given the area's important role for Kenya's total employment and food production, understanding agricultural production in this area is thus of broader policy relevance.

As indicated in the summary statistics in Table 1, mean agricultural output of each household amounts to around 38 000 KShs (≈ 550 US\$)⁵⁴ subject to some variation. Generally, the farmers living in the area are poor by international standards: a majority live on less than 2 US\$/capita per day and 30-40% of the population are below the poverty line (<1 US\$/cap./day). Consequently, the level of technology is very low (hoe and panga only for tilling) and the amount of agricultural inputs is also very low.

⁵⁴ 1 US\$ \approx 70 KShs.

Table 1. Summary of Descriptive Statistics

Variable	Variable definition	Mean	Min.	Max.	Std Dev
Q	Output (KShs)	38313	2050	304450	43252
L _Q	Labour supply: Agric. (h/yr)	1407	90	6060	980
F	Chem. Fertilizer (KShs)	3504	0	14400	2543.8
P	Pesticides (KShs)	211	0	18000	1235
M	Manure (KShs)	6343	0	40000	7428
K	Ag. Land area (acres)	2.4	0.2	8.0	1.3
I ₁	Green manure (rating 0-10)	0.8	0	8	1.9
I ₂	Terrace quality (rating 0-10)	5.8	0	10	2
I ₃	Distance coffee factory (m)	2011	100	12000	1835
I ₄	Tree capital (nr coffee trees)	144	0	526	97
H ₁	Sex of Head (1=M; 0=F)	0.7	0	1	0.5
H ₂	Age of Head (years)	55.1	20	96	13.9
H ₃	Education of Head (years)	5.7	0	20	4.4
H ₄	Livestock capital (KSh)	23778	0	150250	20729
H ₅	Age of coffee trees (years)	22.4	0	54	11.6
H ₆	Family size (nr. members)	4.2	1	13	2.2

Labour constitutes the major input (> 1400 hours per year). Although there is some variation, the average farm spends only around 10 000 KShs (\approx 140 US\$) per year on chemical fertilizers, pesticides and manure. As an indicator of land scarcity and fragmentation, the mean land area used for agricultural production by each household is only 2.4 acres,⁵⁵ cultivated by four family members on average. Due to subdivision, the farms in the area are distributed in narrow strips sloping downwards from sharp ridges. A typical farm stretches from the ridge crest some 100-150 meters down to the slope base at the valley bottom until it reaches a stream or a river. The slopes are steep with mean farm-gradients ranging between 20-60%. The homestead is typically located at the crest around which garden fruits and vegetables are cultivated.

The largest share of the agricultural land is allocated to food crops like maize, beans, potatoes, kale (*sukuma wiki*), and bananas. Minor food crops include yams, sorghum and cassava. Tree crops grown and sold include papaya, avocado, macadamia nuts and mangoes. A sizeable share of the farm area is allocated for cash crop production,

⁵⁵ The mean farm size is 2.8 acres; some land is allocated to the homestead, grazing, woodlots or classified as wasteland.

which implies mono-cultivation of coffee (*Arabica*) on bench terraces. Around the homestead fruits and vegetables like lemon, lime, oranges and mango, and tomatoes, cabbage and lettuce are cultivated.

Although most of the agricultural activities are carried out by women, 70% of the households are headed by older men (mean age 55 years). The remaining 30% consist of widows, divorced women or women headed households where the men are more or less permanently working elsewhere. The level of formal education is low; slightly more than half of the adults can read and write and average years of schooling is less than six years. Although poverty is widespread, most households possess some livestock capital. As indicated in Table 1, the variation between households is considerable. Nevertheless, mean livestock capital holding amounts to 24 000 KShs (\approx 340 US\$). This usually includes a cow, one or two goats and some poultry. Distance to public infrastructure is long. For instance, the distance to the nearest coffee factory is on average more than 2 km, typically characterised by hilly and slippery rural foot trails. Coffee (like most crops) is carried to the factories (or the local market) as headloads in sacks. Even though the major source of income is on-farm agriculture, many of the households also obtain income from on-farm non-agricultural work or off-farm work.⁵⁶

Table 2 below shows some summary statistics of the soil properties. The main soil type cultivated in the area is the reddish humic Nitisol. This soil has developed from weathered basic volcanic rock. It is generally categorized as fertile and clayish, but is prone to strong leaching and erosion, which reduce fertility considerably (Sombroek et al., 1982).

Based on geographical comparisons and laboratory analysis (Thomas, 1997), the soil samples statistics indicate that the soils in the study area are generally acidic, moderate in carbon and organic matter, and have low cation exchange capacity.

⁵⁶ *On-farm non-agricultural work* usually include activities like brewing, brick-making, baking, pottery, shoe-making, wood carving, repairs, sewing or similar practical low-skill types of work. *Off-farm incomes* are derived from work as a guard, driver, running a small shop, hawking, casual labourer on others' farms or *semi-skilled work* in small-scale grain mills, coffee factories, or milk- and fruit-processing plants, or in some few cases *skilled work* as school teacher, nurse etc.

Table 2. Summary Statistics of Soil Properties

Soil property	Unit	Mean	Min.	Max.	Std. Dev.
pH-level (H ₂ O solution)	-log H ⁺	5.63	4.1	8.2	0.66
Carbon (C)	%	1.51	0.16	2.81	0.45
Organic matter	%	2.59	0.28	4.83	0.78
Nitrogen (N)	%	0.18	0.08	0.6	0.06
Potassium (K)	m.eq./100 g.	2.36	0.15	11	1.73
Sodium (Na)	m.eq./100 g.	0.14	0	0.6	0.19
Calcium (Ca)	m.eq./100 g.	6.48	1.45	20	3.29
Magnesium (Mg)	m.eq./100 g.	5.26	0.02	17.42	2.81
Cation Exchange Capacity	m.eq./100 g.	15.69	0	36.8	5.49
Phosphorus (P)	ppm	17.84	1	195	24.67
Texture: Sand	%	16.4	5	50	6.85
Texture: Clay	%	63.16	28	82	10.59

Despite information of this kind, it is difficult to say something *a priori* about the soil's productivity or fertility. The difficulty arises partly because crops respond very differently to different proportions and absolute amounts of soil properties, partly because each crop is endogenously chosen and adapted to each plot. Besides the impacts of external factors such as rainfall, temperature and sunlight, the difficulty is compounded by soils' and crops' different responses to various (combinations of) inputs like mineral fertilizers and farm-yard manure (Thomas, 1997; Gachene and Kimaru, 2003). Consequently, the outcomes are individually unique and "soil productivity" is essentially an empirical issue.

For our purposes, it is of interest to identify agricultural output given the actual distribution of soil properties and farming system (crop mix, choice of inputs etc.) observed in each farm.

3. Choice of Model

In our model we assume the farmers to produce output (Q) by a specific choice of traditional economic production factors (Z), other variables (I) and soil capital (S). As indicated in equation (1) below we assume a modified translog function⁵⁷:

$$(1) \quad \ln(Q) = \alpha + \sum_i \beta_i \ln(Z_i) + \frac{1}{2} \sum_i \sum_j \beta_{ij} \ln(Z_i) \ln(Z_j) + \sum_k \gamma_k I_k + \sum_l \delta_l \ln(S_l) + u$$

where the first part is a traditional translog with conventional economic variables (labour, capital etc.), expanded in the second part with investments (I) and soil capital (S). α , β_i , β_{ij} , γ_k and δ_l are the parameter coefficients to be estimated. u denotes the error term; it is assumed to be normally distributed and represents unexplained factors like rainfall, sunlight and temperature.

Z is a vector of traditional agricultural physical inputs including labour (L), fertilizers (F), manure (M) and agricultural land (K). Arguably, these inputs are independent of the error term since most of the decisions on the type, amount and use of inputs are made prior to the time output is realised. The physical inputs of these production factors are chosen in different proportions by the farmer and are thus variable in the short run. Hence, Z is a choice variable.

I is a vector of variables pertaining to soil conservation investments, access to public infrastructure, and tree capital. S represents original, underlying properties of the soil. Although we lack data on these particular properties, we have data on certain soil properties (S_l ; $l=1..n$), which may serve as proxies for S . However, as shown in Ekbohm (2007) these soil properties are functions of other variables:

$$(2) \quad \hat{S}_l = f(\mathbf{H}, \mathbf{I}, X, \mathbf{PF}, \mathbf{R}),$$

⁵⁷ Indeed, many functional forms are conceivable, but since the true technology is unknown and cannot be determined a priori, the choice of appropriate functional form is essentially an empirical issue (Guilkey *et al.*, 1983). Our choice is motivated by the fact that the translog is flexible (Christensen *et al.*, 1973; Simmons and Weiserbs, 1979) and has been used in many empirical investigations of agricultural production (see e.g. Sherlund *et al.* (2002), Jacoby (1992; 1993), Skoufias (1994) and Gerdin (2002)).

where \mathbf{H} represents a vector of household characteristics, \mathbf{I} is a vector of variables representing soil conservation investments, X represents technical extension advice provided to farmers on soil and water conservation, and \mathbf{PF} is a vector of physical production factors used in the agriculture. \mathbf{R} is a vector representing variables on crop allocation. Equation 1 and 2 thus represent a recursive system, which implies that we should use \hat{S}_l as substitutes for S_l . Hence, the empirical estimations will be based on the following equation:

$$(3) \quad \ln(\hat{Q}) = \alpha + \sum_i \beta_i \ln(Z_i) + \frac{1}{2} \sum_i \sum_j \beta_{ij} \ln(Z_i) \ln(Z_j) + \sum_k \gamma_k I_k + \sum_l \delta_l \ln(\hat{S}_l) + u.$$

Qualitatively, the rationale behind estimating equation 3 instead of equation 1 is due to the possibility that some variables have an impact on output directly while others have both a direct effect and an indirect effect via their effect on soil (S).

The factors represented by I and S might be altered in the long run, but are fixed in the short run. This assumption stipulates separability between Z , I and S in the estimations. The definition of each variable is given a more thorough explanation in section 3.

In order to estimate equation 3, we regress eq. (2) and (3) in two steps: first, we produce predicted values of S_l by Seemingly Unrelated Regression (SUR)-analysis of equation 2; second, we estimate equation 3 by OLS after inclusion of the predicted values of soil capital (\hat{S}_l) as instrumental variables (IV) for S_l .⁵⁸ Regularity conditions of the translog production imply that *linear homogeneity* and *symmetry* will be satisfied if: $\sum_i \beta_i = 1$, $\sum_i \beta_{ij} = 0$ and $\beta_{ij} = \beta_{ji}$ for $i, j = 1, \dots, n$ and *monotonicity* is satisfied if the estimated factor shares are positive.⁵⁹ In the econometric specification we impose linear homogeneity and symmetry.⁶⁰

⁵⁸ Using this method introduces a problem with respect to the standard deviations when using the predicted values of S in the right hand side. However, we argue that this problem is small in this case since the results in the sensitivity test do not change much when we use the actual values of S .

⁵⁹ Concavity is satisfied if the Hessian matrix of second-order derivatives is negative semi-definite (i.e. its eigenvalues are non-positive). This regularity condition can however not be fulfilled here; production in some farms yield negative output elasticities. The usual assumption of cost minimization in production cannot be attained in our context, arguably due to imperfect information on e.g. soil

As point of departure we use a comprehensive set of variables believed to explain agricultural output (see section 4 below) in order to estimate a universal model (UM) of equation 3. We use Likelihood ratio tests as a formal method of model choice, by nesting two restricted models and testing down from the universal model. The first restricted model (RM1) includes a sub-set of the variables included in UM (including the predicted values of soil capital, and soil conservation investments). The other restricted model (RM2) includes only “traditional” economic variables⁶¹, namely agricultural labour, fertilizers, manure and land.

Even in a seemingly homogeneous setting, individual conditions may vary considerably. We therefore estimate individual output elasticities for each household.

As a sensitivity test of model robustness, we also perform regression analysis of equation 1 where S_i is represented by actual field measures of soil capital, i.e. chemical and physical soil properties such as pH, carbon, nitrogen, phosphorus, potassium and grain size-distribution.

4. Data Collection and Definition of Variables

The data used in our analysis is obtained from a household survey collected in 1998. Based on a random sample, 252 small-scale farm households were identified and interviewed between June and August in 1998. The interviewed farms constitute approximately 20% of the total number of farms in the study area.

Output (Q): The farmers in the area produce approximately 30 different crops on farms of various sizes. They produce on average six crops per farm. Output is aggregated using local market prices. The value of agricultural output produced by

status at the farm level. Soil capital and soil conservation technologies are also fixed in the short term and can therefore not be used in optimal proportions.

⁶⁰ The specific restrictions imposed on the model are the following: $\beta_1 + \beta_2 + \beta_3 + \beta_4 = 1$; $\beta_{11} + 0.5*\beta_{12} + 0.5*\beta_{13} + 0.5*\beta_{34} = 0$; $0.5*\beta_{12} + \beta_{22} + 0.5*\beta_{23} + 0.5*\beta_{24} = 0$; $0.5*\beta_{13} + 0.5*\beta_{23} + \beta_{33} + 0.5*\beta_{34} = 0$; $0.5*\beta_{14} + 0.5*\beta_{24} + 0.5*\beta_{34} + \beta_{44} = 0$. For estimation statistics of the translog model restrictions, see appendix 5 and 7, respectively.

⁶¹ $\ln(Q)_{RM2} = \alpha + \sum_i \beta_i \ln(Z_i) + \frac{1}{2} \sum_i \sum_j \beta_{ij} \ln(Z_i) \ln(Z_j) + \varepsilon$

each household (Q) is derived by multiplying each household's physical production of crop i (q_i) by the local market price (p_i): $Q = \sum p_i q_i$. Coffee is the main cash crop. Maize, beans, potatoes, kale (*sukuma wiki*) and bananas are the key food or subsistence crops. Output from agro-forestry or tree crops like mangos, avocado, lemons, papaya and macadamia nuts are included in aggregated output.

*Labour, fertilizer and manure:*⁶² Agricultural labour (L_Q) includes all labour supplied to agricultural production activities like seed-bed preparation, sowing, weeding, thinning and harvesting. It is measured by number of hours supplied during the last year of cultivation, covering two growing seasons. It includes labour supplied by adult family labour and hired labour. It excludes labour allocated to soil conservation investments like digging cut-off drains or maintaining terraces. This is motivated by the fact that soil conservation is a long-term effort with inter-temporal impacts picked up by S and I .

Farmers use inorganic fertilizers, which are supplied on the market in different brands, chemical compositions and physical units. Farmers also use farm-yard manure from poultry or livestock in their cultivation. Due to heterogeneity in physical units and types, production factors like fertilizers and manure, and output are aggregated by their local market price (c_i), respectively: $F = \sum c_i F_i$ and $M = \sum c_i M_i$.

Soil capital: Data on soil capital (S_i) were obtained from physical soil samples collected during the same period in all farms. The soil samples were taken at 0-15 cm depth from the topsoil, based on three replicates in each farm field (*shamba*). Places where mulch, manure and chemical fertilizer were visible were avoided for soil sampling. The soil samples were air dried and analysed at the Department of Soil Science (DSS), University of Nairobi.⁶³ Analysis of correlation coefficients showed

⁶² Although some farmers (approximately 15%) also use pesticides in their production, pesticides are not included in the model since there are strong reasons to believe that pests are part of the error term; pests are commonly treated re-actively (ie mitigated when a pest has broken out and has been observed) and may be correlated with other inputs.

⁶³ Total nitrogen (N) was analyzed by the Kjeldahl method. Potassium (K) was determined using flame photometer. Available phosphorus (P) was analyzed using the Mehlich method. Further details of the standard analytical methods used at the DSS can be found in Okalebo *et al.* (1993), Ekbohm and Ovuka (2001) and Ovuka (2000).

correlation between some soil properties (see Appendix 1). In order to avoid multicollinearity the restricted model (RM1) includes only uncorrelated soil properties.

Soil conservation investments (I): The data on soil conservation investments are defined in terms of a quality rating. The rating is derived from a practical expert assessment framework for evaluating soil conservation technologies (described in Thomas (1995) and Thomas et al. (1997)). The soil conservation technologies are measured in terms of a rating scaled from 0-10 according to standard criteria for quality assessment by field technical assistants. Generally, higher rating implies higher quality of specific conservation investments to arrest soil erosion, prevent land degradation and maintain soil moisture and fertility. The specific soil conservation technologies used in the econometric analysis (green manure, terraces) constitute a sub-set of a larger data set of soil conservation variables (Appendix 2). They are common soil conservation technologies in the area, and represent both biological conservation measures (green manure) and physical measures (terraces).

Green manure (I₁) is a form of conservation tillage. It is a biological conservation technology to enhance agricultural productivity. Practicing green manure is a soil capital investment which, in general terms, builds up the soil's physical, chemical, structural and biological properties. Specifically, it implies planting of cover crops, (e.g. legumes or grasses), with the combined purposes of reducing the soil's erodibility, increasing organic matter content, building up the soil's physical structure, maintaining soil moisture and improving the soil's fertility. It is of interest to study since it has the potential to boost yields *and* conserve soil (Mureithi et al., 2003). Green manure is practiced as part of an integrated nutrient management system (Woomer et al., 1999).

Soil conservation terraces (I₂) in Kenya typically imply excavated (backward sloping) bench terraces or terraces established by throwing soil up-hill (*fanya juu*) or down-hill (*fanya chini*) to form soil bunds along the contour. As soil erodes they gradually develop into full terraces. Commonly, grasses of various types⁶⁴ are cultivated on top

⁶⁴ Napier-, Guatemala- or elephant-grass.

of the terrace embankment to stabilize the terrace edges and reduce soil loss (Thomas et al, 1997).

Access to public infrastructure (I₃): Information, transportation and transactions costs may be important but elusive factors for agricultural production (Obare *et al*, 2003). Hence, as a proxy we use “distance to nearest coffee factory” (measured in meters) to represent these factors in the model estimations. Access to public infrastructure is included in the model due to the effect it may have on farmers’ production decisions and conditions including e.g. crop composition, marketing opportunities, availability of inputs, and access to advice and information.

Tree capital (I₄): All farmers in the sample cultivate coffee. Generally, they possess very little capital. Besides soil conservation structures, the coffee trees represent a major investment in their farming system. Due to the potential importance of this investment, the number of coffee trees are included in the model as a proxy for capital.

Some of the observations in the data are zero-valued. This introduces a problem in the estimation of a translog functional form. In line with the convention in much of the translog literature (see Sherlund *et al.*, 2002), we set $\ln(0)=0$.

5. Statistical Results

The estimates of agricultural production yield some interesting results. First, Likelihood Ratio (LR)-tests⁶⁵ show that model RM1, which includes standard agricultural input variables, predicted values of soil capital (*S*) and conservation investments variables (*I*), fit the data significantly better than the other models. As indicated in table 3 below, the restricted model (RM1) is preferred over the universal model (UM). Table 3 also shows that inclusion of more soil capital variables and household characteristics provide a better fit than the more parsimonious “traditional” economic model (RM2) including only labour, fertilizer, manure and agricultural

⁶⁵ LR is a statistical test of goodness of fit between models and provides an objective criterion for selecting among possible models (Greene, 2000).

land. Interestingly, table 3 also shows that the universal model (UM) fit the data significantly better than the parsimonious model (RM2).

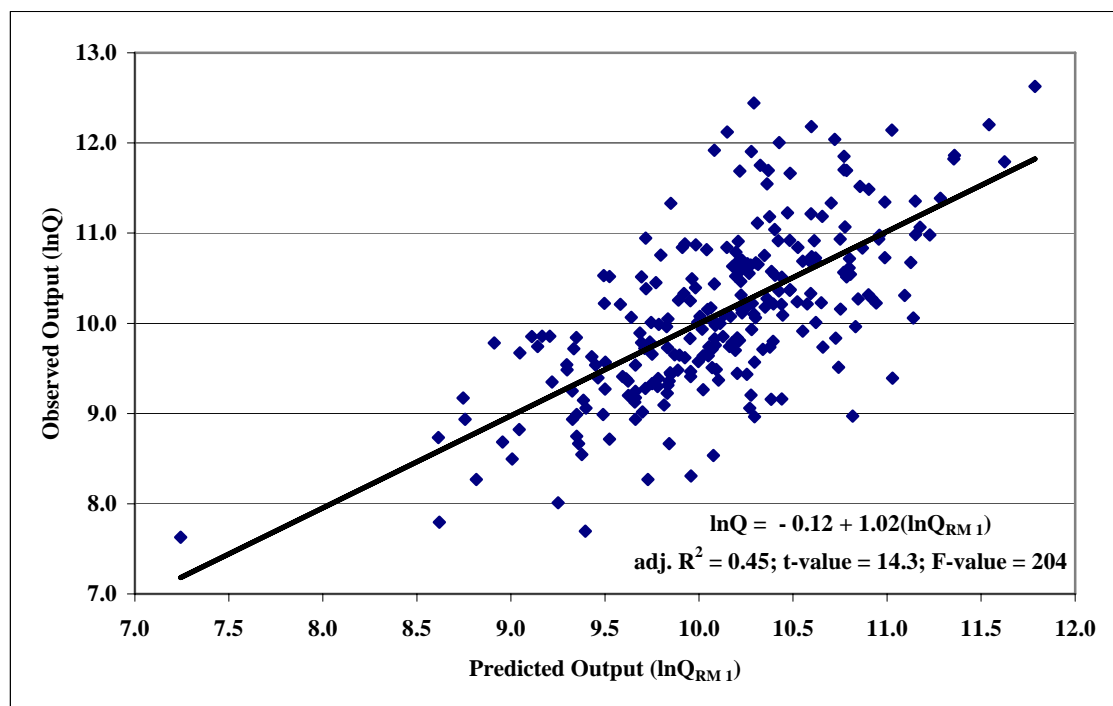
Table 3. Likelihood Ratio tests of models

Model	Log Likelihood (-lnL)	Compared models	LR	DF	CV (p=0.01)	Result
UM	252.0	RM1 vs UM	16.0	12	26.2	Accept
RM1	260.0	RM2 vs RM1	55.5	10	23.2	Reject
RM2	287.8	RM2 vs UM	71.5	22	40.3	Reject

LR=Likelihood Ratio, DF= Degrees of Freedom, CV=Critical value; Accept: CV>LR; Reject: CV<LR

Acknowledging that R-square is not defined for this type of model, we present figure 2 below to illustrate goodness of fit of the restricted model (RM1) for predicted and observed output, respectively.

Figure 2: Predicted Output and Observed Output



Further, the output elasticities in Table 4 below indicate that inclusion of soil capital and investment variables in UM and RM1 yield partly different output elasticities⁶⁶ compared to the most restricted model (RM2). This difference in results suggests that inclusion of new relevant explanatory variables contribute to change (increase or decrease the size of) the output elasticities produced by the traditional agricultural production function represented by RM2. As we are interested in the role and contribution of soil capital and (the quality of) soil conservation investments, our focus is on interpreting RM 1.

Table 4. Mean Output Elasticities of Explanatory Variables

Output Elasticity	Definition	UM		RM1		RM2	
		Estimate	t-value	Estimate	t-value	Estimate	t-value
$\hat{\epsilon}_{\hat{Q}_L}$	Labour elasticity	0.131	1.23	0.114	1.09	0.000	0.01
$\hat{\epsilon}_{\hat{Q}_F}$	Fertilizer elasticity	0.254	3.01	0.272	3.31	0.277	3.39
$\hat{\epsilon}_{\hat{Q}_M}$	Manure elasticity	0.141	2.01	0.150	2.30	0.243	3.95
$\hat{\epsilon}_{\hat{Q}_K}$	Land elasticity	0.475	3.22	0.464	3.31	0.479	3.59
$\hat{\epsilon}_{\hat{Q}_{I_1}}$	Green Manure elasticity	0.130	1.20	0.131	1.67		
$\hat{\epsilon}_{\hat{Q}_{I_1}}$	Terrace conservation elasticity	0.188	1.45	0.204	1.65		
$\hat{\epsilon}_{\hat{Q}_{I_2}}$	Access infrastructure elasticity	-0.134	-2.11	-0.131	-2.36		
$\hat{\epsilon}_{\hat{Q}_{I_3}}$	Tree capital elasticity	0.043	1.27	0.064	1.99		
$\hat{\epsilon}_{\hat{Q}_{S_1}}$	Nitrogen elasticity	0.290	1.70	0.273	1.62		
$\hat{\epsilon}_{\hat{Q}_{S_2}}$	Potassium elasticity	0.450	1.57	0.352	1.78		
$\hat{\epsilon}_{\hat{Q}_{S_3}}$	Phosphorus elasticity	-0.266	-2.25	-0.220	-2.30		

Agricultural labour: The mean output elasticity of *labour* is insignificant in all models and practically zero in the most restricted model (RM2). Although statistically insignificant, this result points at the labour abundance (high per capita-land ratio) in the area and the low marginal productivity of labour.

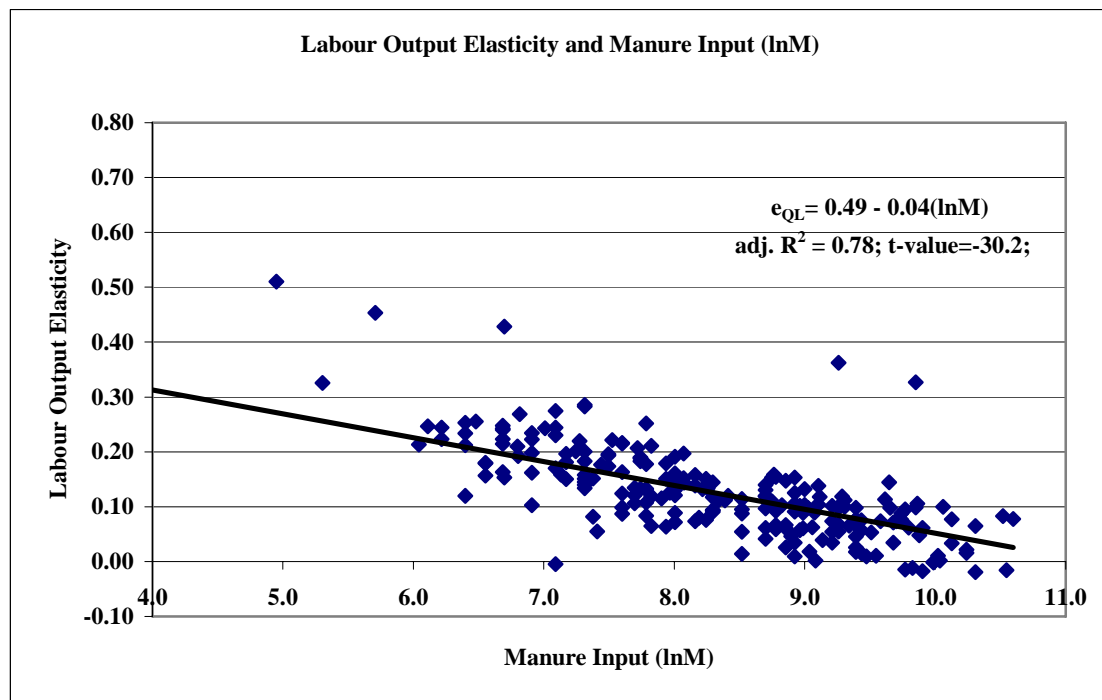
Interestingly, the regression results of the parameter estimates indicate a substitution effect between agricultural labour and farm-yard manure. Plotting the individual

⁶⁶ Individual and mean output elasticities are calculated by using the following formula (we use agricultural labour input (L_Q) in the universal model (UM) to exemplify):

$$\hat{\epsilon}_{\hat{Q}_L}^{UM} = \frac{\partial \ln(\hat{Q})}{\partial \ln(L_Q)} = \beta_1 + 2 * \beta_{11} \ln(L_Q) + \beta_{12} \ln(F) + \beta_{13} \ln(M) + \beta_{14} \ln(K) = 0.131$$

output elasticities of labour against those of manure input (Figure 3 below) confirms the negative inter-action effect observed in all models (presented in Appendix 4). This might be explained by specialization in farming activities. Farmers who use little or no manure typically increase their labour supply to cultivation, and vice versa. Interestingly, a similar negative relationship applies to labour and fertilizer. Agronomic studies, which exclude labour input, would typically not pick up this result.

Figure 3: Output Elasticity of Agricultural Labour and Manure input (KSh)



Chemical fertilizer and manure: The output elasticities of chemical fertilizer and manure in Table 4 and in the parameter estimates in Appendix 4 indicate that they are both positively associated with crop output. This applies to all of the three estimated models and is in accord with the lion's share of the economic literature on determinants of agricultural production in developing countries (see e.g. Mundlak *et al.* 1997; Fulginiti and Perrin, 1998, Sherlund *et al.*, 2002). The output elasticity of fertilizer is relatively stable across the models, whereas the output elasticity of manure goes down around 40% in the models including soil capital and investments (UM and RM1).

Agricultural land: We note from the table of elasticities that the mean output elasticity of agricultural land is generally higher than the other output elasticities. The output elasticity of land is relatively stable across the models and does not change significantly as we restrict the universal model. The individual elasticities indicate that households with smaller plots generally have higher output per unit area. The theory on benefit from economies of scale suggests that the opposite result would be expected. However, our result is plausible if farmers intensify production as farms become smaller. The result is also in accord with other studies in similar settings (see e.g. Heltberg, 1998). These results reflect the intensification in land use currently taking place in Kenya. Land fragmentation into smaller and smaller plots push farmers away from their land and forces the remaining farmers to intensify their land use.

Green manure: Well managed green manure is positively associated with crop output ($\varepsilon_{Q_1}^{RM1} = 0.13$). This result accords with other relevant studies (see e.g. Onim et al., 1990; Raquet, 1990; Peoples and Craswell, 1992; Fischler and Wortmann, 1999; Mureithi et al., 1998, 2002, 2003). To exemplify, Mureithi *et al.* (1998, 2000) report that farmers in Thika District, in Kenya's central highlands, significantly increase their maize yields after incorporation of legumes into the soil. Similarly, Onyango *et al.* (2001) find positive effects on crop yield of green manure legumes intercropped with maize in smallholder farms in Kenya's western highlands.

Arguably, the positive elasticity of green manure is due to the positive effects legumes have on the soil's chemical, biological and physical properties. Several studies show that cultivation and incorporation of legumes into the soil increases ground cover, prevents soil loss, reduces infestation of weeds and plant diseases, prevents leaching, supplies additional nitrogen, improves soil tilth and water infiltration, builds up soil fertility, and enhances crop productivity (Yost and Evans, 1988; Lal *et al.*, 1991; Hudgens, 2000; Gachene and Kimaru, 2003).

Soil conservation terraces: The output elasticities show that high-quality soil conservation terraces are positively associated with crop output. Specifically, the output elasticity of terrace conservation for the restricted model (RM1) is significant

and relatively large ($\varepsilon_{\hat{Q}I_2}^{RM1} = 0.20$). This positive relationship corresponds with other results from the region, see e.g. Kilewe (1987), Gachene (1995), Pagiola (1999) and Stephens and Hess (1999).

Access to public infrastructure: Table 4 shows that shorter distance to public infrastructure promotes agricultural output ($\varepsilon_{\hat{Q}I_3}^{RM1} = -0.13$).⁶⁷ The particular result that closer distance to the coffee factory is associated with higher output is plausibly explained by the following factors: coffee factories provide essential crop management-advice and other information to farmers⁶⁸; coffee factories sell inputs like insecticides and fertilizers and offer credits of various types; closer access may induce farmers to change their crop composition in favour of higher-value crops. Due to the opportunity cost of time for transport, more closely located factories provide the advice and inputs more cheaply to farmers who reside nearby. The result points at the importance of easily accessed coffee factories. This may be attained by an expansion of the number of coffee factories and input supplies, intensified extension advice, and/or improved road infrastructure and public transport in rural areas (Obare *et al.*, 2003).

Soil Capital: The models including instrumental variables of soil capital (UM, RM1) show generally that the output elasticities of (the predicted values of) nitrogen and potassium are positive. Compared with other inputs such as manure, they are relatively large: regarding the predicted value of nitrogen $\varepsilon_{\hat{Q}\delta_1}^{RM1} = 0.27$ and potassium $\varepsilon_{\hat{Q}\delta_2}^{RM1} = 0.35$, respectively. Counter to our expectations, the output elasticity of phosphorus is negative ($\varepsilon_{\hat{Q}\delta_3}^{RM1} = -0.22$). A possible explanation to this result is the fact that additional supply of inorganic phosphorus in acidic soils reduces pH even further, which inhibits plants' uptake of P (due to quick fixation) and hence reduces the crop yield. Negative yield effects of this type are typically observed on strongly leached and/or eroded clayish soils, which have been subject to: continuous application of

⁶⁷ The result applies specifically to access to coffee factories. However, we obtain negative signs on the parameter estimates and negative output elasticities for *all* types of public infrastructure collected in the data set.

⁶⁸ Staff at the coffee factories professionally assess the quality of delivered coffee and commonly provide information on means to improve productivity, and detect and prevent pests like coffee berry disease.

inorganic (NPK) fertilizers over several years, continuous cropping and limited (insufficient) supply of organic matter (Gachene and Kimaru, 2003). In fact, these conditions characterize our study area: due to immediate food and income needs, fallowing is seldom practiced; high relative prices on farm-yard manure (FYM; due to high transport costs and limited market supply) force farmers to buy inorganic fertilizers instead of increasing their use FYM, which is recommended to improve crop yields *and* sustained soil productivity. Moreover, negative output effects of increased supply of P are observed when it inhibits uptake of essential micro nutrients like zinc (Zn) and copper (Cu). Deficiency in these soil elements quickly results in retarded leaf and shoot growth, and stunted plant development. However, explaining the negative output effect of P is complicated even further by the fact that i) application of organic manure (which includes P) reduces acidity and promotes plants' uptake of both macro- and micro-nutrients, and ii) liming increases pH, reduces the toxicity of high aluminium (Al) availability, increases P availability and micro-biological activity, and promotes crop productivity.

In view of these facts, determining the specific reasons to the negative sign of the phosphorus elasticity requires more site-specific soil sample data and further study.⁶⁹ Nonetheless, the negative phosphorus elasticity points at a typical information problem associated with poverty. As opposed to farmers in developed countries, the farmers in our study area are deprived of three kinds of services:

First, they lack access to appropriate soil analysis and specific information on the status of their soil capital (nutrient levels etc.). The situation is characterized by asymmetric information where farmers typically lack formal (scientific) information on their soil capital.⁷⁰ On the other hand, they have practical knowledge gained from experience.

Second, the farmers lack access to a broad set of fertilizers appropriate for the farm-specific agro-ecological conditions. The local fertilizer market offers only few varieties with fixed proportions between the key nutrients. The farmer's possibilities

⁶⁹ Personal communication, Gete Zeleke, Charles Gachene, Frank Place and Anna Tengberg.

⁷⁰ The lack of scientific information is also relevant for crops, where farmers could benefit from plant-tissue analysis and interpretation (Gachene and Kimaru, 2003).

to choose among many varieties and finetune in accord with crop-specific requirements are limited. The most common type of chemical fertilizer used in the study area is di-ammonium phosphate (DAP) with the typical NPK-distribution⁷¹ of 20:20:0, calcium ammonium nitrate (CAN) with the typical NPKCa-distribution of 20:20:0:13, and to a lesser extent NPK 17:17:17. All of these have relatively high P contents and low or no K content. Consequently, the farmers contribute to lower soil pH, which is already low (acidic), and hence impede plant growth.

Third, the farmers are dependent on sub-optimal advice. Besides neighbours and relatives, the farmers primarily obtain advice on agriculture and land use from two sources: local stockists and government extension agents. The stockists are usually local monopolists in the supply of agricultural physical inputs. According to the farmers and stockists in the study area, the stockists frequently give advice on how and when to use their products (e.g. chemical fertilizers, pesticides, improved seeds) despite limited *specific* knowledge on the individual farmer's soil and agro-ecological conditions.

Although the government's extension agents can provide more reliable information than the stockists, they also lack specific information on what fertilizers would be appropriate for the individual farmer. Due to limited geographical coverage, infrequent visits and lack of farm-specific information (obtained from e.g. soil sample analysis), the extension advice tends to be rather general. Due to these obstacles, the farmers cannot optimize their fertilizer input and crop composition in the same way as in modern agriculture. The fact that all observed farmers use inorganic fertilizers, which reduce pH is an indication of their lack information on enhanced soil management and/or access to other inputs (e.g. lime) which may improve soil fertility.

Assessing Kenya's fertilizer consumption across time (presented in Table 5), the percentage shares of N, P and K have been relatively stable. The percentage share of P as part of total fertilizer consumption is very large (around 50%). Conversely, the share of K has remained at a low level (5-10%). In 2002, it was only 2%. The

⁷¹ The percentage distribution of refers to P₂O₅ (inorganic P) and K₂O (inorganic K). Hence, 20:20:0 corresponds to 20% N, 20% P₂O₅, 0% K₂O plus ballast. For conversion to percentage *weight* distribution, inorganic P = 0.436 x (P₂O₅); elemental K = 0.83 x (K₂O).

relatively low share of K and the relatively high share of P are surprising and somewhat counter-intuitive, given the positive output elasticity of K, and the negative output elasticity of P.

Table 5. Fertilizer consumption in Kenya 1962-2002 (% share of total NPK consumption)

	1962	1972	1982	1992	2002
Nitrogen (N)	29%	35%	44%	47%	40%
Phosphorus (P)	62%	53%	49%	45%	58%
Potassium (K)	9%	12%	6%	8%	2%

Source: FAO, 2005. *FAOSTAT data base* (<http://apps.fao.org/faostat/>), Rome.

In view on our statistical findings and the increasing use of inorganic fertilizers in Kenya⁷² on acidic soils (which impedes soil nutrient uptake and optimal plant growth), it is essential that Kenya's fertilizer use and soil nutrient-output relationships are addressed in a comprehensive policy analysis. It is also noticeable that very few farmers report use of buffering fertilizers like rock phosphate or lime, despite potentials to ameliorate acidic soils and increase crop production (Rutunga *et al.*, 1998).

Sensitivity Analysis

As a sensitivity test of our basic results we estimate the productivity equation (1) using the direct observed soil properties (S_i) instead of the predicted values (\hat{S}_i). As we can see from table 7 and 8, the differences compared with the earlier results are small and in no case significant. Further, as indicated in Table 8, it does not alter the previous outcome of the Likelihood Ratio test.

⁷² Although Kenya's total consumption of inorganic fertilizer is low compared to developed countries, consumption of NPK-fertilizer has increased rapidly during last 40 years. In 1961, Kenya's total consumption of NPK was 1 100 metric tons. In 2002, it had increased to 143 000 metric tons (FAO, 2005).

Table 7. Mean Output elasticities of explanatory variables based on models using actual soil properties (UM', RM1') and RM2

Output		UM'		RM1'		RM2	
Elasticity	Definition	Estimate	t-value	Estimate	t-value	Estimate	t-value
ϵ_{QLQ}	Labour elasticity	0.108	1.11	0.084	0.88	0.000	0.01
ϵ_{QF}	Fertilizer elasticity	0.194	2.42	0.203	2.57	0.277	3.39
ϵ_{QM}	Manure elasticity	0.154	2.38	0.165	2.70	0.243	3.95
ϵ_{QK}	Land elasticity	0.544	4.23	0.547	4.32	0.479	3.59
ϵ_{QI_1}	Green Manure elasticity	0.240	3.10	0.202	2.70		
ϵ_{QI_1}	Terrace conservation elasticity	0.283	2.30	0.248	2.14		
ϵ_{QI_2}	Access infrastructure elasticity	-0.121	-1.94	-0.125	-2.25		
ϵ_{QI_3}	Tree capital elasticity	0.041	1.03	0.072	2.28		
ϵ_{QS_1}	Nitrogen elasticity	0.293	1.71	0.278	1.63		
ϵ_{QS_2}	Potassium elasticity	0.232	1.75	0.262	2.01		
ϵ_{QS_3}	Phosphorus elasticity	-0.173	-2.33	-0.145	-1.98		

Table 8. Likelihood Ratio test of models using actual soil properties (UM', RM1') and RM2

Model	Log Likelihood (-lnL)	Compared models	LR	DF	CV (p=0.01)	Result
UM	253.9	RM1' vs UM'	24.4	12	26.2	Accept
RM 1	266.1	RM2 vs RM1'	43.4	10	23.2	Reject
RM 2	287.8	RM2 vs UM'	67.8	22	40.3	Reject

LR=Likelihood Ratio, DF= Degrees of Freedom, CV=Critical value; Accept: CV>LR; Reject: CV<LR

However, one difference that is worth mentioning is the fertilizer elasticity. In UM' and RM1' the fertilizer elasticity is around 0,20 which is somewhat (although not significantly) lower than the corresponding elasticity for the simplest model RM2 with no variables on soil capital and soil conservation investments. If one were to look only at these OLS estimates, one might be tempted to draw the conclusion that omission of soil properties had given us too high a value of the fertilizer elasticity. However, the instrumental variable analysis shows that the elasticity is not affected at all. This can be interpreted as follows: fertilizer application has a direct effect on yield together with other variables and also an indirect long run effect through improvements in soil status. The latter connection is discussed in Ekbohm (2007). Results may be biased if we do not take this into account: If we use the observed soil characteristics (S_i) in the regression we get a biased estimate and some of the effect that should be attributed to the fertilizer gets wrongly attributed to the soil characteristics.

This illustrates the importance, in principle of using instrumental variables although in this particular case, it did not have any major or significant effect on the parameters of any of the main variables.

Finally, all estimates of the translog restrictions (linear homogeneity and symmetry) imposed in the models are found to be statistically insignificant. This indicates that the restrictions do not introduce any major distortions in the suggested models.

6. Summary and Conclusions

This study has methodological, empirical and policy results. Starting with the methodological we show that integrating traditional economics and soil science is highly worthwhile in this area of research. Omitting key variables in the analysis such as measures of soil capital can cause omitted variables bias since farmers' choice of inputs depend both on the quality and status of the soil capital and on other economic conditions such as availability and cost of labour, fertilizers and other inputs.

We complement a traditional economic production function model (including labour, fertilizers, manure and land) with specific soil properties, quality measures of soil and water conservation investments and some other variables related to extension advice, access to public infrastructure and capital. Based on econometric analysis of data from individual farmer interviews and soil sample data in Kenya's central highlands, comparison between a universal model including all potentially relevant variables and two restricted models, yields several useful results: First, major soil nutrients are important explanatory factors; nitrogen (N) and potassium (K) increase output strongly, whereas higher phosphorus (P) levels are actually detrimental to output. This points at the importance of ensuring adequate fertilizer policies, adjusted to the local bio-physical conditions, and access to a broad set of fertilizers in the local market. Second, introduction of soil properties is associated with a decrease in the output elasticities of and farm-yard manure. Exclusion of soil properties and soil conservation technologies introduces the risk of biased coefficients of the other variables. Third, only the output elasticity of land contributes more to output than N

and K. The output elasticity of fertilizer is relatively smaller. This points at the importance of including soil capital in economic analyses of agricultural output. Our sensitivity analysis furthermore shows that the results are fairly robust.

A fourth result is that soil conservation technologies like terraces and green manure contribute to increase agricultural output even in models that also include soil properties and chemical fertilizer. Given the policy debate on the impact and usefulness of government subsidies to soil conservation, our results suggest that soil conservation investments contribute to increase farmers' output. Consequently, government support to appropriate soil conservation investments, like green manure and terraces, not only arrest soil erosion, it also assists farmers' efforts to increase food production and reduce food insecurity. A final result is that since the bio-physical variables contribute to explain agricultural output, traditional economic analyses need to reconsider the opportunities associated with larger integration of soil capital and investments in land among the explanatory variables.

Two central policy conclusions emanate from this study: First, while fertilizers are generally beneficial, their application is a complex art, and more is not necessarily better: negative phosphorus elasticities indicate that application of more P on these soils may in fact reduce crop yield. In modern agriculture it is standard practice to test soil properties on individual plots in order to select the appropriate fertilizer amounts and proportions. It seems that this practice might be truly beneficial in Kenya's agricultural production as well. Although farmers in many instances possess vast local soil knowledge (Winklerprins, 1999), there is a need to integrate this with scientific information on soil capital, and strengthen farmers' access to research-based agricultural extension services.

Second, farmers and extension agents currently lack the means and the specific knowledge necessary to pursue optimal agriculture, i.e. crop cultivation which is highly productive, profitable and maintaining soil capital across time. There is thus a need to strengthen the links to the applied research and increase the use of integrated soil and land-use assessment based on both farmers' knowledge, experiences, needs and preferences, *and* scientific knowledge. Relevant research-based services which may be offered to farmers include e.g. formal soil sample analysis, expert judgment

on optimal farming systems and land use, farm-specific soil mapping, plant-tissue analysis etc. We argue that the government has a special responsibility in providing these opportunities in rural areas. One might argue that if yields can be raised or risks of crop failure be reduced by a better use of soil testing and thus more informed fertilizer selection, then the market should start offering such services (soil testing combined with increased fertilizer supply and extension advice).

Currently, however, these services are not offered. Arguably, this is due to a combination of several factors: The *technical (chemical) complexities* of the issues and the difficulty of communicating them to farmers, who lack sufficient knowledge in this area; *asymmetric information* between farmers and the private sector potentially offering soil and land-management services; *thin markets* – verging on virtual monopolies on supply of inputs at the local level and *high investment risks* for private companies, which might offer farm-specific services. From the farmers' point of view, demand for soil sample analysis does not occur naturally or easily, arguably due to *poverty, risk aversion and high discount rates*. Since practical experiences and extension advice are lacking in this area, the farmers are also *uncertain or unaware of the opportunities* associated with soil management based on soil sample analysis, which would function as a complement to their own knowledge and experiences. For all these reasons, it seems appropriate that the government should at least initially take the lead in this area by speeding up its provision of farm-specific soil assessment, services for enhanced soil management and facilitate development of markets for it.

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Appendix 1. Correlation Coefficients of Soil Properties

Variables	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	S ₇	S ₈	S ₉	S ₁₀	S ₁₁
S₁ Nitrogen	1	0.05	0.04	0.06	-0.12	-0.01	0.09	-0.03	-0.12	0.02	0.59
		<i>0.47</i>	<i>0.56</i>	<i>0.34</i>	<i>0.05</i>	<i>0.88</i>	<i>0.15</i>	<i>0.61</i>	<i>0.07</i>	<i>0.70</i>	<i><.0001</i>
S₂ Potassium		1.00	0.10	0.12	-0.14	-0.02	0.08	-0.04	0.23	0.26	0.14
			<i>0.10</i>	<i>0.05</i>	<i>0.03</i>	<i>0.77</i>	<i>0.19</i>	<i>0.56</i>	<i>0.00</i>	<i><.0001</i>	<i>0.03</i>
S₃ Phosphorus			1.00	0.07	-0.12	0.35	0.36	0.26	-0.10	0.36	0.06
				<i>0.26</i>	<i>0.06</i>	<i><.0001</i>	<i><.0001</i>	<i><.0001</i>	<i>0.11</i>	<i><.0001</i>	<i>0.31</i>
S₄ Sand				1.00	-0.88	0.00	-0.05	-0.06	0.14	0.00	0.15
					<i><.0001</i>	<i>0.94</i>	<i>0.42</i>	<i>0.31</i>	<i>0.03</i>	<i>0.94</i>	<i>0.02</i>
S₅ Clay					1.00	-0.14	-0.07	-0.09	-0.11	-0.15	-0.23
						<i>0.02</i>	<i>0.29</i>	<i>0.17</i>	<i>0.07</i>	<i>0.02</i>	<i>0.00</i>
S₆ Calcium						1.00	0.53	0.74	-0.14	0.79	-0.05
							<i><.0001</i>	<i><.0001</i>	<i>0.03</i>	<i><.0001</i>	<i>0.41</i>
S₇ pH							1.00	0.57	-0.19	0.59	-0.02
								<i><.0001</i>	<i>0.00</i>	<i><.0001</i>	<i>0.81</i>
S₈ Magnesium								1.00	-0.16	0.84	-0.16
									<i>0.01</i>	<i><.0001</i>	<i>0.01</i>
S₉ Sodium									1.00	-0.10	0.00
										<i>0.12</i>	<i>0.95</i>
S₁₀ Cation Exchange Capacity										1.00	-0.03
											<i>0.64</i>
S₁₁ Carbon											1.00

Appendix 2. Correlation Coefficients of Soil Conservation Quality variables (1-12)

Nr.	Variable	1	2	3	4	5	6	7	8	9	10	11	12
1	Cut-off drains	1	0.34	0.326	0.236	-0.044	0.09	0.111	0.19	0.41	0.214	0.201	0.446
			<i><.0001</i>	<i><.0001</i>	<i>0.0004</i>	<i>0.515</i>	<i>0.186</i>	<i>0.103</i>	<i>0.005</i>	<i><.0001</i>	<i>0.002</i>	<i>0.003</i>	<i><.0001</i>
2	Crop cover		1	0.342	0.162	0.101	0.203	0.082	0.094	0.3	0.131	0.082	0.351
				<i><.0001</i>	<i>0.017</i>	<i>0.136</i>	<i>0.003</i>	<i>0.229</i>	<i>0.166</i>	<i><.0001</i>	<i>0.054</i>	<i>0.226</i>	<i><.0001</i>
3	Tillage practices			1	0.401	-0.08	-0.076	0.04	0.05	0.37	0.192	0.171	0.362
					<i><.0001</i>	<i>0.237</i>	<i>0.261</i>	<i>0.56</i>	<i>0.465</i>	<i><.0001</i>	<i>0.004</i>	<i>0.012</i>	<i><.0001</i>
4	Manure				1	0.121	0.081	0.072	0.056	0.45	0.134	0.23	0.285
						<i>0.074</i>	<i>0.236</i>	<i>0.289</i>	<i>0.41</i>	<i><.0001</i>	<i>0.048</i>	<i>0.001</i>	<i><.0001</i>
5	Crop residue management					1	0.403	0.418	-0.012	0.06	-0.1	0.035	0.089
							<i><.0001</i>	<i><.0001</i>	<i>0.855</i>	<i>0.4</i>	<i>0.147</i>	<i>0.608</i>	<i>0.19</i>
6	Mulching						1	0.433	0.05	0.1	0.063	0.046	0.182
								<i><.0001</i>	<i>0.463</i>	<i>0.1</i>	<i>0.352</i>	<i>0.501</i>	<i>0.007</i>
7	Green manure							1	0.041	0.16	0.153	0.041	0.128
									<i>0.55</i>	<i>0</i>	<i>0.024</i>	<i>0.545</i>	<i>0.059</i>
8	Agro-forestry								1	0.17	0.183	0.642	0.315
										<i>0</i>	<i>0.007</i>	<i><.0001</i>	<i><.0001</i>
9	Fodder management									1	0.266	0.262	0.357
											<i><.0001</i>	<i><.0001</i>	<i><.0001</i>
10	Grazing land management										1	0.249	0.157
												<i>0</i>	<i>0.021</i>
11	Fuel wood											1	0.223
													<i>0.001</i>
12	Terraces												1

Appendix 3: Definition of Variables

Q	= Crop output (KSh)
\hat{Q}	= Predicted Crop output (KSh)
Z	= Vector of traditional agricultural production factors
I	= Vector of exogenous explanatory variables
S	= Soil capital; vector of soil properties
$f()$	= Function of determinants
K	= Agricultural land area (acres)
L_Q	= Labour supply to agricultural production (mandays)
F	= Fertilizer input (KSh)
M	= Manure input (KSh)
PF	= Physical production factors
H	= Household characteristics
R	= Crop allocation area
X	= Provision of technical extension advice
c	= Vector of factor prices associated with F and M
β	= Parameter coefficient of production factors associated with Z
γ	= Parameter coefficients of associated with I
δ	= Parameter coefficients of associated with S
α	= Intercept
u	= Error term
p_i	= Price of crop i
q_{ih}	= Physical production of crop i by household h
k_h	= Agricultural farm area (in acres) for household h
p	= Crop price
ε	= Output elasticity with respect to production factors

Appendix 4: Regression results of models UM, RM1, RM2

Param.	Code	Independent variable	UM		RM1		RM2	
			Estimate	t-value	Estimate	t-value	Estimate	t-value
α	INT	Intercept	7.448	2.64	8.371	3.25	6.323	2.67
β_1	$\ln L_Q$	$\ln(\text{Ag. Labour input})$	-0.482	-0.61	-0.343	-0.44	-0.091	-0.12
β_2	$\ln F$	$\ln(\text{Chem. Fertilizer})$	0.040	0.21	0.124	0.68	0.138	0.72
β_3	$\ln M$	$\ln(\text{Manure})$	0.070	0.52	0.072	0.54	0.181	1.34
β_4	$\ln K$	$\ln(\text{Land})$	1.371	1.61	1.147	1.38	0.772	0.94
β_{11}	$\ln L_Q * \ln L_Q$	$\ln(\text{Labour input: squared})$	0.082	1.24	0.082	1.28	0.064	1.01
β_{22}	$\ln F * \ln F$	$\ln(\text{Fertilizer: squared})$	0.016	1.50	0.018	1.73	0.021	1.96
β_{33}	$\ln M * \ln M$	$\ln(\text{Manure: squared})$	0.012	1.69	0.012	1.88	0.021	3.21
β_{44}	$\ln K * \ln K$	$\ln(\text{Land: squared})$	0.073	0.96	0.056	0.76	0.025	0.35
β_{12}	$\ln L_Q * \ln F$	$\ln(\text{Labour}) \times \ln(\text{Fertilizer})$	-0.014	-0.45	-0.034	-1.10	-0.033	-1.02
β_{13}	$\ln L_Q * \ln M$	$\ln(\text{Labour}) \times \ln(\text{Manure})$	-0.031	-1.57	-0.034	-1.77	-0.052	-2.62
β_{14}	$\ln L_Q * \ln K$	$\ln(\text{Labour}) \times \ln(\text{Land})$	-0.118	-0.85	-0.097	-0.72	-0.042	-0.32
β_{23}	$\ln F * \ln M$	$\ln(\text{Fertilizer}) \times \ln(\text{Manure})$	0.008	0.92	0.011	1.23	0.004	0.52
β_{24}	$\ln F * \ln K$	$\ln(\text{Fertilizer}) \times \ln(\text{Land})$	-0.026	-0.78	-0.014	-0.41	-0.014	-0.39
β_{34}	$\ln M * \ln K$	$\ln(\text{Manure}) \times \ln(\text{Land})$	-0.001	-0.04	-0.001	-0.05	0.007	0.27
γ_1	I_1	$\ln(\text{Green manure})$	0.130	1.20	0.131	1.67		
γ_2	I_2	$\ln(\text{Terrace quality})$	0.188	1.45	0.204	1.65		
γ_3	I_3	$\ln(\text{Access public infrastr.})$	-0.134	-2.11	-0.131	-2.36		
γ_4	I_4	$\ln(\text{Tree capital})$	0.043	1.27	0.064	1.99		
δ_1	$\ln \hat{S}_N$	$\ln(\text{Nitrogen (N) in soil})$	0.495	0.55	0.343	0.39		
δ_2	$\ln \hat{S}_K$	$\ln(\text{Potassium (K) in soil})$	-0.565	-1.14	-0.579	-1.22		
δ_3	$\ln \hat{S}_P$	$\ln(\text{Phosphorus (P) in soil})$	0.401	1.10	0.330	0.96		
δ_{11}	$\ln \hat{S}_N \times \ln \hat{S}_N$	$\ln(\text{Nitrogen}) \times \ln(\text{Nitrogen})$	0.066	0.25	0.023	0.09		
δ_{22}	$\ln \hat{S}_K \times \ln \hat{S}_K$	$\ln(\text{Potass.}) \times \ln(\text{Potass.})$	0.628	1.82	0.576	1.77		
δ_{33}	$\ln \hat{S}_P \times \ln \hat{S}_P$	$\ln(\text{Phosph.}) \times \ln(\text{Phosph.})$	-0.149	-1.67	-0.123	-1.54		
δ_4	$\ln \hat{S}_4$	Sand in soil (%)	0.017	1.08				
δ_5	$\ln \hat{S}_5$	Clay in soil (%)	0.008	0.81				
δ_6	$\ln \hat{S}_6$	Calcium (Ca) (meq/100 g)	0.004	0.20				
δ_7	$\ln \hat{S}_7$	Soil pH (H ₂ O)	0.105	1.03				
δ_8	$\ln \hat{S}_8$	Magnesium (Mg) (meq/100 g)	-0.011	-0.38				
δ_9	$\ln \hat{S}_9$	Sodium (Na) (meq/100 g)	-0.014	-0.05				
γ_5	I_5	Sex of Head (M=1; F=0)	0.011	0.09				
γ_6	I_6	Age of HH head (years)	0.006	0.99				
γ_7	I_7	Education Head (yrs.)	-0.007	-0.46				
γ_8	I_8	Livestock capital (KSh)	0.000	2.51				
γ_9	I_9	Age of coffee trees (years)	0.006	0.22				
γ_{10}	I_{10}	Family size (nr. members)	0.030	1.32				
	<i>R-square</i>			0.47		0.43		0.31
	<i>Adj. R-square</i>			0.39		0.39		0.28
	<i>MSE</i>			0.51		0.52		0.59

Appendix 5a: Estimates of Translog Restrictions on UM, RM1, RM2

Restrictions	UM		RM1		RM2	
	Estimate	t-value	Estimate	t-value	Estimate	t-value
$\beta_1 + \beta_2 + \beta_3 + \beta_4 = 1$	7.5	1.21	-1.4	-0.21	-7.6	-1.10
$\beta_{11} + 0.5*\beta_{12} + 0.5*\beta_{13} + 0.5*\beta_{34} = 0$	94.8	1.11	-20.7	-0.22	-101.3	-1.07
$0.5*\beta_{12} + \beta_{22} + 0.5*\beta_{23} + 0.5*\beta_{24} = 0$	104.5	1.11	-39.6	-0.38	-134.5	-1.26
$0.5*\beta_{13} + 0.5*\beta_{23} + \beta_{33} + 0.5*\beta_{34} = 0$	45.2	0.45	-81.3	-0.76	-128.7	-1.19
$0.5*\beta_{14} + 0.5*\beta_{24} + 0.5*\beta_{34} + \beta_{44} = 0$	21.2	1.40	-1.6	-0.10	-13.1	-0.78

Appendix 5b. Pearson Correlation Coefficients of Output Elasticities of Agricultural Production Variables

Output		Output Elasticities						
Elasticity	Definition	$\varepsilon_{\hat{Q}_L}$	$\varepsilon_{\hat{Q}_F}$	$\varepsilon_{\hat{Q}_M}$	$\varepsilon_{\hat{Q}_K}$	$\varepsilon_{\hat{Q}_{S_1}}$	$\varepsilon_{\hat{Q}_{S_2}}$	$\varepsilon_{\hat{Q}_{S_3}}$
$\varepsilon_{\hat{Q}_L}$	Labour elasticity	1.00	-0.58	-0.91	0.02	-0.04	-0.06	0.21
			<.0001	<.0001	-0.6996	-0.5123	-0.3446	-0.0011
$\varepsilon_{\hat{Q}_F}$	Fertilizer elasticity		1.00	0.32	-0.09	-0.05	-0.07	-0.07
				<.0001	-0.1492	-0.4004	-0.286	-0.3041
$\varepsilon_{\hat{Q}_M}$	Manure elasticity			1.00	-0.32	0.09	0.08	-0.24
					<.0001	-0.1564	-0.1843	<.0001
$\varepsilon_{\hat{Q}_K}$	Land elasticity				1.00	-0.08	0.01	0.08
						0.1884	0.9282	0.1971
$\varepsilon_{\hat{Q}_{S_1}}$	Nitrogen elasticity					1.00	-0.14	-0.14
							0.0247	0.0312
$\varepsilon_{\hat{Q}_{S_2}}$	Potassium elasticity						1.00	0.15
								0.018
$\varepsilon_{\hat{Q}_{S_3}}$	Phosphorus elasticity							1.00

n = 252

Appendix 6: Regression results of models UM', RM1' and RM2

Param.	Code	Independent variable	UM'		RM1'		RM2	
			Estimate	t-value	Estimate	t-value	Estimate	t-value
α	INT	Intercept	6.451	2.32	7.301	2.93	6.323	2.67
β_1	lnL _Q	ln(Ag. Labour input)	-0.116	-0.15	0.011	0.01	-0.091	-0.12
β_2	lnF	ln(Chem. Fertilizer)	0.019	0.10	0.111	0.61	0.138	0.72
β_3	lnM	ln(Manure)	0.093	0.69	0.077	0.58	0.181	1.34
β_4	lnK	ln(Land)	1.004	1.23	0.801	1.02	0.772	0.94
β_{11}	lnL _Q * lnL _Q	ln(Labour input: squared)	0.043	0.69	0.049	0.80	0.064	1.01
β_{22}	lnF * lnF	ln(Fertilizer: squared)	0.015	1.38	0.014	1.35	0.021	1.96
β_{33}	lnM * lnM	ln(Manure: squared)	0.014	2.08	0.015	2.38	0.021	3.21
β_{44}	lnK * lnK	ln(Land: squared)	0.037	0.52	0.020	0.30	0.025	0.35
β_{12}	lnL _Q * lnF	ln(Labour) x ln(Fertilizer)	-0.007	-0.22	-0.029	-0.95	-0.033	-1.02
β_{13}	lnL _Q * lnM	ln(Labour) x ln(Manure)	-0.029	-1.48	-0.036	-1.86	-0.052	-2.62
β_{14}	lnL _Q * lnK	ln(Labour) x ln(Land)	-0.050	-0.38	-0.032	-0.25	-0.042	-0.32
β_{23}	lnF * lnM	ln(Fertilizer) x ln(Manure)	0.001	0.12	0.008	0.95	0.004	0.52
β_{24}	lnF * lnK	ln(Fertilizer) x ln(Land)	-0.023	-0.70	-0.007	-0.21	-0.014	-0.39
β_{34}	lnM * lnK	ln(Manure) x ln(Land)	0.001	0.03	-0.002	-0.07	0.007	0.27
γ_1	I ₁	ln(Green manure)	0.240	3.10	0.202	2.70		
γ_2	I ₂	ln(Terrace quality)	0.283	2.30	0.248	2.14		
γ_3	I ₃	ln(Access public infrastr.)	-0.121	-1.94	-0.125	-2.25		
γ_4	I ₄	ln(Tree capital)	0.041	1.03	0.072	2.28		
δ_1	lnS _N	ln(Nitrogen (N) in soil)	0.023	0.03	-0.052	-0.06		
δ_2	lnS _K	ln(Potassium (K) in soil)	-0.051	-0.64	-0.037	-0.46		
δ_3	lnS _P	ln(Phosphorus (P) in soil)	-0.218	-1.42	-0.217	-1.42		
δ_{11}	lnS _N x lnS _N	ln(Nitrogen) x ln(Nitrogen)	-0.087	-0.33	-0.106	-0.41		
δ_{22}	lnS _K x lnS _K	ln(Potass.) x ln(Potass.)	0.102	1.72	0.108	1.81		
δ_{33}	lnS _P x lnS _P	ln(Phosph.) x ln(Phosph.)	0.015	0.49	0.025	0.81		
δ_4	lnS ₄	Sand in soil (%)	0.019	1.22				
δ_5	lnS ₅	Clay in soil (%)	0.008	0.77				
δ_6	lnS ₆	Calcium (Ca) (meq/100 g)	0.014	0.60				
δ_7	lnS ₇	Soil pH (H ₂ O)	0.113	1.14				
δ_8	lnS ₈	Magnesium (Mg) (meq/100 g)	-0.011	-0.38				
δ_9	lnS ₉	Sodium (Na) (meq/100 g)	-0.064	-0.24				
γ_5	I ₅	Sex of Head (M=1; F=0)	0.134	1.17				
γ_6	I ₆	Age of HH head (years)	-0.002	-0.39				
γ_7	I ₇	Education Head (yrs.)	-0.022	-1.65				
γ_8	I ₈	Livestock capital (KSh)	0.000	3.05				
γ_9	I ₉	Age of coffee trees (years)	0.001	0.25				
γ_{10}	I ₁₀	Family size (nr. members)	0.035	1.59				
	<i>R-square</i>			0.47		0.42		0.31
	<i>Adj. R-square</i>			0.39		0.37		0.28
	<i>MSE</i>			0.51		0.53		0.59
	<i>SSE</i>			111.5		122		144.8

Appendix 7: Estimates of Translog Restrictions on UM', RM1', RM2

Restrictions	UM'		RM 1'		RM 2	
	Estimate	t-value	Estimate	t-value	Estimate	t-value
$\beta_1 + \beta_2 + \beta_3 + \beta_4 = 1$	6.9	1.08	-1.7	-0.24	-7.6	-1.10
$\beta_{11} + 0.5*\beta_{12} + 0.5*\beta_{13} + 0.5*\beta_{34} = 0$	82.9	0.94	-26.7	-0.28	-101.3	-1.07
$0.5*\beta_{12} + \beta_{22} + 0.5*\beta_{23} + 0.5*\beta_{24} = 0$	101.2	1.05	-40.5	-0.39	-134.5	-1.26
$0.5*\beta_{13} + 0.5*\beta_{23} + \beta_{33} + 0.5*\beta_{34} = 0$	41.0	0.40	-91.6	-0.84	-128.7	-1.19
$0.5*\beta_{14} + 0.5*\beta_{24} + 0.5*\beta_{34} + \beta_{44} = 0$	19.3	1.24	-2.5	-0.15	-13.1	-0.78

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