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

Anders Ekbom and Thomas Sterner[1]

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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Keywords: micro analysis of farm firms, resource management. JEL classification: Q12, Q20

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1. Introduction

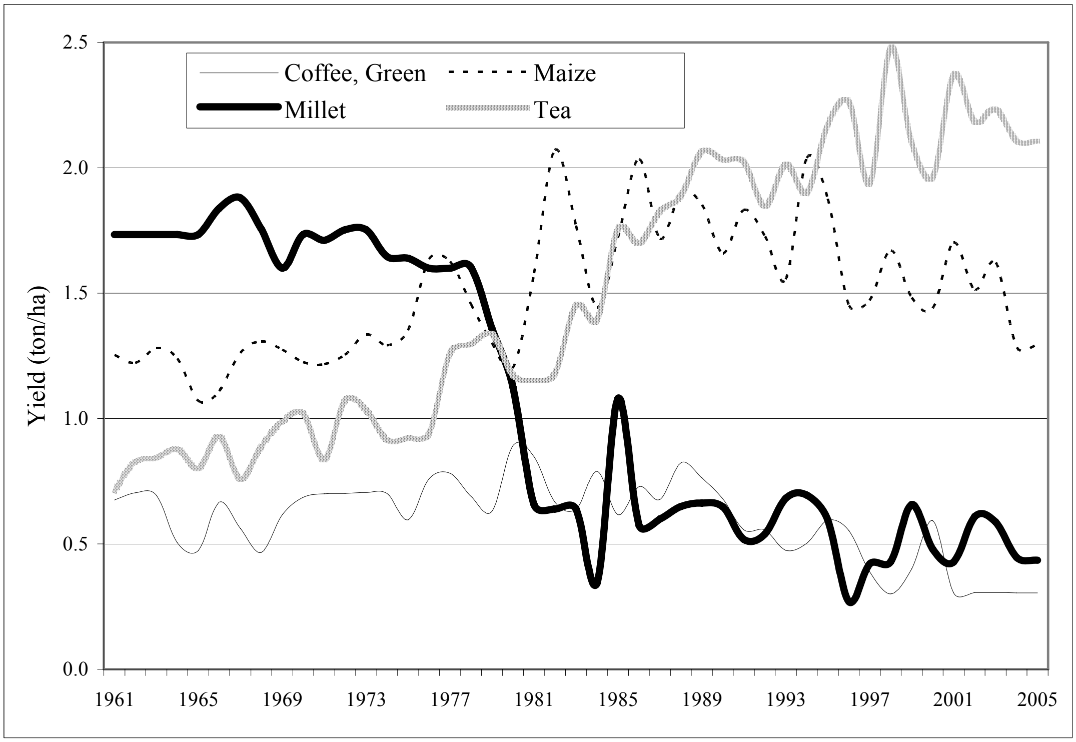
The purpose of this paper is to increase our understanding of the determinants of agricultural production by integrating models and methods from economics and soil science. The rationale for this paper is the opportunity to synthesise two areas of analysis: economic studies typically do not include soil 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. (0º43' S, 37º07' 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$)[2] subject to some variation. Generally, the farmers living in the area are poor by international standards: a majority live on less than 2 US$/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.

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[2] 1 US$ ≈ 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 (≈ 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,[3] cultivated by four family members on average. Due to sub-division, 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, 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.

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

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. Mean livestock capital holding amounts to 24 000 KShs (≈ 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.[4]

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).

Table 2. Summary Statistics of Soil Properties

Soil property	Unit	Mean	Min.	Max.	Std. Dev.
pH-level (H_20 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

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[4] *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.

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. 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 function[5]:

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

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

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[5] 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)).

physical inputs of these production factors are choosen 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 Ekbom (2007) these soil properties are functions of other variables:

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

where ***H*** represents a vector of household characteristics, ***I*** is a vector of variables representing soil conservation investments, *X* represents technical extension advice provided to farmers on soil and water conservation, and ***PF*** is a vector of physical production factors used in the agriculture. ***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) $$\ln(\hat{Q}) = \alpha + \sum_i \beta_i \ln(Z_i) + \frac{1}{2}\sum_i \sum_j \beta_{ij} \ln(Z_i)\ln(Z_j) + \sum_k \gamma_k I_k + \sum_l \delta_l \ln(\hat{S}_l) + u \cdot$$

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. 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, …, n* and *monotonicity* is satisfied if the estimated factor shares are positive.[6] In the econometric specification we impose linear homogeneity and symmetry.[7]

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 variables[8], 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_t 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.

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[6] 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 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.

[7] 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.

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

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 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:[9] 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_l) 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.[10] Analysis of correlation coefficients showed correlation

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[9] 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.

[10] 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), Ekbom and Ovuka (2001) and Ovuka (2000).

between some soil properties (see Appendix 1). In order to avoid multi-collinearity 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 (I_1) 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. Specificially, 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 (I_2) 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 types[11] are cultivated on top of the terrace embankment to stabilize the terrace edges and reduce soil loss (Thomas et al, 1997).

Access to public infrastructure (I_3)*:* 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

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[11] Napier-, Guatemala- or elephant-grass.

farmers' production decisions and conditions including e.g. crop composition, marketing opportunities, availability of inputs, and access to advice and information.

Tree capital (I_4)*:* 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)-tests[12] 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 prefered 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 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.

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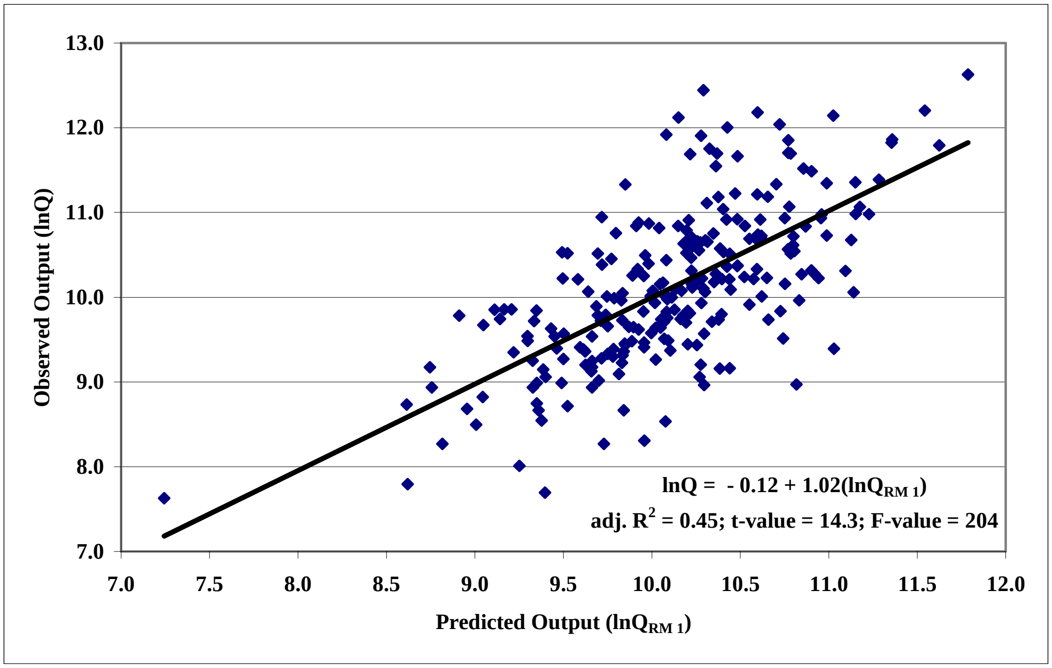
[12] LR is a statistical test of goodness of fit between models and provides an objective criterion for selecting among possible models (Greene, 2000).

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 elasticities[13] 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.

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[13] Indiv $\varepsilon_{\hat{Q}L_{\hat{Q}}}$ idual and mean output elasticities are calculated by using the following formula (we use agricultural labour input $\left(L_Q\right)$ in the universal model (UM) to exemplify):

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

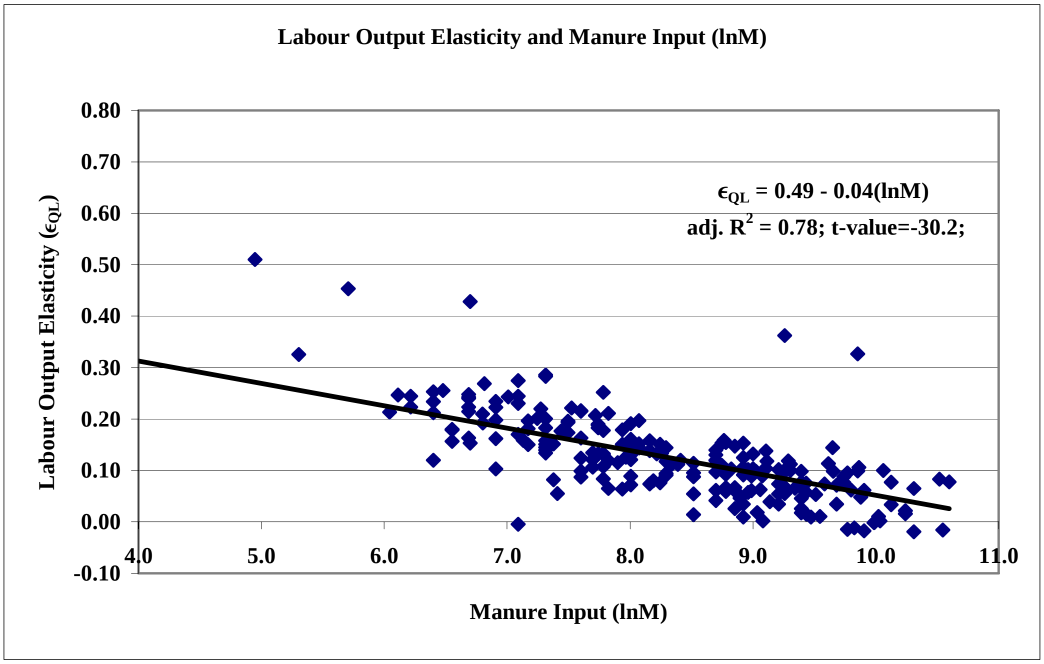
Table 4. Mean Output Elasticities of Explanatory Variables

Output Elasticity	Definition	UM Estimate	UM t-value	RM1 Estimate	RM1 t-value	RM2 Estimate	RM2 t-value
$\varepsilon_{\hat{Q}L_{\hat{Q}}}$	Labour elasticity	0.131	1.23	0.114	1.09	0.000	0.01
$\varepsilon_{\hat{Q}F}$	Fertilizer elasticity	0.254	3.01	0.272	3.31	0.277	3.39
$\varepsilon_{\hat{Q}M}$	Manure elasticity	0.141	2.01	0.150	2.30	0.243	3.95
$\varepsilon_{\hat{Q}K}$	Land elasticity	0.475	3.22	0.464	3.31	0.479	3.59
$\varepsilon_{\hat{Q}I_1}$	Green Manure elasticity	0.130	1.20	0.131	1.67		
$\varepsilon_{\hat{Q}I_1}$	Terrace conservation elasticity	0.188	1.45	0.204	1.65		
$\varepsilon_{\hat{Q}I_2}$	Access infrastructure elasticity	-0.134	-2.11	-0.131	-2.36		
$\varepsilon_{\hat{Q}I_3}$	Tree capital elasticity	0.043	1.27	0.064	1.99		
$\varepsilon_{\hat{Q}\hat{S}_1}$	Nitrogen elasticity	0.290	1.70	0.273	1.62		
$\varepsilon_{\hat{Q}\hat{S}_2}$	Potassium elasticity	0.450	1.57	0.352	1.78		
$\varepsilon_{\hat{Q}\hat{S}_3}$	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 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 ($\varepsilon_{\hat{Q}I_1}^{RM1} = 0.13$). 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 ($\varepsilon_{\hat{Q}I_3}^{RM1} = -0.13$).[14] 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 farmers[15]; 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).

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[14] 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.

[15] 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.

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 $\varepsilon_{\hat{Q}\hat{S}_1}^{RM1} = 0.27$ and potassium $\varepsilon_{\hat{Q}\hat{S}_2}^{RM1} = 0.35$, respectively. Counter to our expectations, the output elasticity of phosphorus is negative ($\varepsilon_{\hat{Q}\hat{S}_3}^{RM1} = -0.22$). 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 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 zink (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.[16] 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.[17] On the other hand, they have practical knowledge gained from experience.

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[16] Personal communication, Gete Zeleke, Charles Gachene, Frank Place and Anna Tengberg.

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

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 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-distribution[18] 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, pestcides, 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 relatively low share of K and the relatively high share of P are

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[18] The percentage distribution of refers to P_2O_5 (inorganic P) and K_2O (inorganic K). Hence, 20:20:0 corresponds to 20% N, 20% P_2O_5, 0% K_2O plus ballast. For conversion to percentage *weight* distribution, inorganic P = 0.436 x (P_2O_5); elemental K = 0.83 x (K_2O).

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 Kenya[19] 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_l) instead of the predicted values ($\hat{S}_l$). 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.

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[19] 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 Elasticity	Definition	UM'		RM1'		RM2	
		Estimate	t-value	Estimate	t-value	Estimate	t-value
ε_{QL_Q}	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 Ekbom (2007). Results may be biased if we do not take this into account: If we use the observed soil characteristics (S_l) 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 inidividual 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 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}
S_1 Nitrogen	**1**	**0.05**	**0.04**	**0.06**	**-0.12**	**-0.01**	**0.09**	**-0.03**	**-0.12**	**0.02**	**0.59**
		0.47	*0.56*	*0.34*	*0.05*	*0.88*	*0.15*	*0.61*	*0.07*	*0.70*	*<.0001*
S_2 Potassium		**1.00**	**0.10**	**0.12**	**-0.14**	**-0.02**	**0.08**	**-0.04**	**0.23**	**0.26**	**0.14**
			0.10	*0.05*	*0.03*	*0.77*	*0.19*	*0.56*	*0.00*	*<.0001*	*0.03*
S_3 Phosphorus			**1.00**	**0.07**	**-0.12**	**0.35**	**0.36**	**0.26**	**-0.10**	**0.36**	**0.06**
				0.26	*0.06*	*<.0001*	*<.0001*	*<.0001*	*0.11*	*<.0001*	*0.31*
S_4 Sand				**1.00**	**-0.88**	**0.00**	**-0.05**	**-0.06**	**0.14**	**0.00**	**0.15**
					<.0001	*0.94*	*0.42*	*0.31*	*0.03*	*0.94*	*0.02*
S_5 Clay					**1.00**	**-0.14**	**-0.07**	**-0.09**	**-0.11**	**-0.15**	**-0.23**
						0.02	*0.29*	*0.17*	*0.07*	*0.02*	*0.00*
S_6 Calcium						**1.00**	**0.53**	**0.74**	**-0.14**	**0.79**	**-0.05**
							<.0001	*<.0001*	*0.03*	*<.0001*	*0.41*
S_7 pH							**1.00**	**0.57**	**-0.19**	**0.59**	**-0.02**
								<.0001	*0.00*	*<.0001*	*0.81*
S_8 Magnesium								**1.00**	**-0.16**	**0.84**	**-0.16**
									0.01	*<.0001*	*0.01*
S_9 Sodium									**1.00**	**-0.10**	**0.00**
										0.12	*0.95*
S_{10} Cation Exchange Capacity										**1.00**	**-0.03**
											0.64
S_{11} 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**
			<.0001	*<.0001*	*0.0004*	*0.515*	*0.186*	*0.103*	*0.005*	*<.0001*	*0.002*	*0.003*	*<.0001*
2	Crop cover		**1**	**0.342**	**0.162**	**0.101**	**0.203**	**0.082**	**0.094**	**0.3**	**0.131**	**0.082**	**0.351**
				<.0001	*0.017*	*0.136*	*0.003*	*0.229*	*0.166*	*<.0001*	*0.054*	*0.226*	*<.0001*
3	Tillage practices			**1**	**0.401**	**-0.08**	**-0.076**	**0.04**	**0.05**	**0.37**	**0.192**	**0.171**	**0.362**
					<.0001	*0.237*	*0.261*	*0.56*	*0.465*	*<.0001*	*0.004*	*0.012*	*<.0001*
4	Manure				**1**	**0.121**	**0.081**	**0.072**	**0.056**	**0.45**	**0.134**	**0.23**	**0.285**
						0.074	*0.236*	*0.289*	*0.41*	*<.0001*	*0.048*	*0.001*	*<.0001*
5	Crop residue management					**1**	**0.403**	**0.418**	**-0.012**	**0.06**	**-0.1**	**0.035**	**0.089**
							<.0001	*<.0001*	*0.855*	*0.4*	*0.147*	*0.608*	*0.19*
6	Mulching						**1**	**0.433**	**0.05**	**0.1**	**0.063**	**0.046**	**0.182**
								<.0001	*0.463*	*0.1*	*0.352*	*0.501*	*0.007*
7	Green manure							**1**	**0.041**	**0.16**	**0.153**	**0.041**	**0.128**
									0.55	*0*	*0.024*	*0.545*	*0.059*
8	Agro-forestry								**1**	**0.17**	**0.183**	**0.642**	**0.315**
										0	*0.007*	*<.0001*	*<.0001*
9	Fodder management									**1**	**0.266**	**0.262**	**0.357**
											<.0001	*<.0001*	*<.0001*
10	Grazing land management										**1**	**0.249**	**0.157**
												0	*0.021*
11	Fuel wood											**1**	**0.223**
													0.001
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

			UM		**RM1**		**RM2**	
Param.	Code	Independent variable	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(Ag. Labour input)	-0.482	-0.61	-0.343	-0.44	-0.091	-0.12
β_2	lnF	ln(Chem. Fertilizer)	0.040	0.21	0.124	0.68	0.138	0.72
β_3	lnM	ln(Manure)	0.070	0.52	0.072	0.54	0.181	1.34
β_4	lnK	ln(Land)	1.371	1.61	1.147	1.38	0.772	0.94
β_{11}	$\ln L_Q * \ln L_Q$	ln(Labour input: squared)	0.082	1.24	0.082	1.28	0.064	1.01
β_{22}	lnF * lnF	ln(Fertilizer: squared)	0.016	1.50	0.018	1.73	0.021	1.96
β_{33}	lnM * lnM	ln(Manure: squared)	0.012	1.69	0.012	1.88	0.021	3.21
β_{44}	lnK * lnK	ln(Land: squared)	0.073	0.96	0.056	0.76	0.025	0.35
β_{12}	$\ln L_Q$ * lnF	ln(Labour) x ln(Fertilizer)	-0.014	-0.45	-0.034	-1.10	-0.033	-1.02
β_{13}	$\ln L_Q$ * lnM	ln(Labour) x ln(Manure)	-0.031	-1.57	-0.034	-1.77	-0.052	-2.62
β_{14}	$\ln L_Q$ * lnK	ln(Labour) x ln(Land)	-0.118	-0.85	-0.097	-0.72	-0.042	-0.32
β_{23}	lnF * lnM	ln(Fertilizer) x ln(Manure)	0.008	0.92	0.011	1.23	0.004	0.52
β_{24}	lnF * lnK	ln(Fertilizer) x ln(Land)	-0.026	-0.78	-0.014	-0.41	-0.014	-0.39
β_{34}	lnM * lnK	ln(Manure) x ln(Land)	-0.001	-0.04	-0.001	-0.05	0.007	0.27
γ_1	I_1	ln(Green manure)	0.130	1.20	0.131	1.67		
γ_2	I_2	ln(Terrace quality)	0.188	1.45	0.204	1.65		
γ_3	I_3	ln(Access public infrastr.)	-0.134	-2.11	-0.131	-2.36		
γ_4	I_4	ln(Tree capital)	0.043	1.27	0.064	1.99		
δ_1	$\ln \hat{S}_N$	ln(Nitrogen (N) in soil)	0.495	0.55	0.343	0.39		
δ_2	Ln $\hat{S}_K$	ln(Potassium (K) in soil)	-0.565	-1.14	-0.579	-1.22		
δ_3	$\ln \hat{S}_P$	ln(Phosphorus (P) in soil)	0.401	1.10	0.330	0.96		
δ_{11}	$\ln \hat{S}_N$ x $\ln \hat{S}_N$	ln(Nitrogen) x ln(Nitrogen)	0.066	0.25	0.023	0.09		
δ_{22}	$\ln \hat{S}_K$ x $\ln \hat{S}_K$	ln(Potass.) x ln(Potass.)	0.628	1.82	0.576	1.77		
δ_{33}	$\ln \hat{S}_P$ x $\ln \hat{S}_P$	ln(Phosph.) x ln(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_2O)	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				
	R-square			*0.47*		*0.43*		*0.31*
	Adj. R-square			*0.39*		*0.39*		*0.28*
	MSE			*0.51*		*0.52*		*0.59*

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

	UM		**RM1**		**RM2**	
Restrictions	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 Elasticity	Definition	Output Elasticities						
		$\varepsilon_{\hat{Q}L_Q}$	$\varepsilon_{\hat{Q}F}$	$\varepsilon_{\hat{Q}M}$	$\varepsilon_{\hat{Q}K}$	$\varepsilon_{\hat{Q}\hat{S}_1}$	$\varepsilon_{\hat{Q}\hat{S}_2}$	$\varepsilon_{\hat{Q}\hat{S}_3}$
$\varepsilon_{\hat{Q}L_Q}$	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*
$\varepsilon_{\hat{Q}\hat{S}_1}$	Nitrogen elasticity					**1.00**	**-0.14**	**-0.14**
							0.0247	*0.0312*
$\varepsilon_{\hat{Q}\hat{S}_2}$	Potassium elasticity						**1.00**	**0.15**
								0.018
$\varepsilon_{\hat{Q}\hat{S}_3}$	Phosphorus elasticity							**1.00**

n = 252

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

			UM'		RM1'		RM2	
Param.	Code	Independent variable	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	$\ln L_Q$	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}	$\ln L_Q * \ln L_Q$	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}	$\ln L_Q * \ln F$	ln(Labour) x ln(Fertilizer)	-0.007	-0.22	-0.029	-0.95	-0.033	-1.02
β_{13}	$\ln L_Q * \ln M$	ln(Labour) x ln(Manure)	-0.029	-1.48	-0.036	-1.86	-0.052	-2.62
β_{14}	$\ln L_Q * \ln K$	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	$\ln S_N$	ln(Nitrogen (N) in soil)	0.023	0.03	-0.052	-0.06		
δ_2	$\ln S_K$	ln(Potassium (K) in soil)	-0.051	-0.64	-0.037	-0.46		
δ_3	$\ln S_P$	ln(Phosphorus (P) in soil)	-0.218	-1.42	-0.217	-1.42		
δ_{11}	$\ln S_N \times \ln S_N$	ln(Nitrogen) x ln(Nitrogen)	-0.087	-0.33	-0.106	-0.41		
δ_{22}	$\ln S_K \times \ln S_K$	ln(Potass.) x ln(Potass.)	0.102	1.72	0.108	1.81		
δ_{33}	$\ln S_P \times \ln S_P$	ln(Phosph.) x ln(Phosph.)	0.015	0.49	0.025	0.81		
δ_4	$\ln S_4$	Sand in soil (%)	0.019	1.22				
δ_5	$\ln S_5$	Clay in soil (%)	0.008	0.77				
δ_6	$\ln S_6$	Calcium (Ca) (meq/100 g)	0.014	0.60				
δ_7	$\ln S_7$	Soil pH (H_2O)	0.113	1.14				
δ_8	$\ln S_8$	Magnesium (Mg) (meq/100 g)	-0.011	-0.38				
δ_9	$\ln S_9$	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				
	R-square			*0.47*		*0.42*		*0.31*
	Adj. R-square			*0.39*		*0.37*		*0.28*
	MSE			*0.51*		*0.53*		*0.59*
	SSE			*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