ENVIRONMENTAL AND ECONOMIC IMPACTS OF SOIL EROSION AND FERTILITY MINING IN NORTHERN TANZANIA

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Introduction

Soil erosion, and soil fertility mining, the practice of growing crops with insufficient replacement of nutrients taken up by the crops, are among the major factors causing agricultural production stagnation in Sub-Saharan Africa (SSA). The incidence of soil erosion and degradation in SSA is higher than in any other part of the world (Lal; Cleaver and Donovan). The major factor contributing to soil degradation has been rapid population growth that has undermined the traditionally sustainable practices of shifting cultivation and transhumant pastoralism. The pressure on land has led to shorter fallows, cultivation on fragile land and overgrazing, which in turn have all accelerated soil erosion. It is estimated that soil erosion affects 65% of cropland in SSA (Dejene, et al.).

Many soils in SSA are inherently of low fertility because the continent is dominated by a geologically old and deeply weathered landscape, making African soils some of the poorest in the world. Chemical fertilizer use has not proved to be a practical solution to the low fertility problem, due in part to poor infrastructure and inefficient input and agricultural product marketing systems, which have resulted in high fertilizer prices that are unaffordable to the resource-poor farmers (Bumb and Baanante). Additionally, the traditional crop varieties used by a majority of farmers in SSA have a low response to fertilizer, making their use even less profitable. Therefore, resource-poor farmers usually grow crops with insufficient replacement of nutrients taken up by crops. Between 1989-93, cropland in SSA received an average of 8 – 12 kg of nitrogen, potassium and phosphorus (NPK)/ha as compared to 83 kg of NPK/ha in all Low income countries. Specifically, in East Africa (Kenya, Tanzania and Uganda), net nutrient removal by crops exceeds replenishment by a factor of three to four (Heisey and Mwangi; Stoorvogel and Smaling).

In Tanzania, an institutional environment of communal ownership of land, which gives the farmer the right to use land without individual title, overlies the soil degradation challenges. The land tenure insecurity implied by common property rights, coupled with relatively expensive inorganic fertilizer hamper land development, husbandry, and in many cases, result in overexploitation of land resources.

Soil Conservation Models

Perhaps the most widely referenced work in the literature of soil conservation economics is by McConnell. The McConnell model used one state variable, soil depth (x) and two control variables, soil erosion (s) and an index of variable inputs, z(t). He assumed that, as farmer expands acreage, more soil is eroded since the farmer is likely to cultivate on more sloped farms. McConnell also assumed that a fixed layer of soil is eroded per unit of land over the entire farmer's planning horizon. Goetz pointed out that, the problem of using soil erosion as a control variable is, soil erosion is a consequence, i.e., an externality, rather than an input, of production. Additionally, if we assume a constant acreage, the control variable vanishes since, with no acreage expansion, soil erosion is zero. Hence McConnell's model does include constant acreage situations where erosion of deeper layers of soil is more important than erosion resulting from acreage expansion.

McConnell argued that the effect of soil quality (soil chemical, physical and biological properties) on crop production is captured by soil depth since he assumed that soil quality is constant. This assumption may not hold for soils that are relatively flat and hence with minimal erosion (Goetz). The assumption may also not hold in SSA where soil fertility mining is an important problem. Hence, soils in SSA may be deep yet of poor quality due to fertility mining. Accounting productivity changes using soil depth only may not capture productivity loss due to poor soil quality. Barbier used soil depth x(t) as state variable, and conventional inputs, z(t), and soil conservation w(t) as control variables. As is the case with McConnell, Barbier assumed a constant soil quality, hence may not be relevant for analyzing soils with high degree of fertility mining.

Goezt modeled soil conservation using a soil erosion function, s(x,z) in the soil depth state variable. Goezt assumed that use of inputs erodes more soils, i.e., $s_z < 0$, and $s_{zz} < 0$. However, this assumption may not hold for some inputs. For instance, Barbier assumed that some inputs may reduce soil erosion while some other may increase soil erosion.

Among the few papers that have addressed soil quality in a dynamic framework is Clarke's. He used soil quality as the state variable that is influenced by the level of production, y(t), variable inputs, z(t), and investment in soil quality improvement, h(t). The control variable h(t) also includes such measures as soil conservation, fertilizer application and other soil degradation control measures. Clarke's model does not separate soil depth from soil quality. Since soil quality and soil depth are embodied in one variable, it may be difficult to analyze policies that have different impacts on soil quality. Additionally, q(t) is linear in h(t). This relationship may be non-linear. For instance, if a farmer constructs contours to control soil erosion, a point will be reached when additional length of contours will have no effect in increasing soil depth, implying that soil erosion function may be concave in contour length.

Model for Analyzing Soil Depth and Quality

This study modifies the models by McConnell, Barbier and Clarke to reflect the problem of soil fertility mining in SSA. A dynamic model that explicitly addresses soil erosion and fertility mining is important for designing land management and improvement policies in SSA.

We use the soil erosion function to model the equation of motion for soil depth, x(t). Unlike most past studies, we assume that the curvature of s(w) may be concave or convex, depending on the type of soil conservation method used. Consider a farmer who attempts to check soil erosion by expending soil conservation efforts, w. Soil conservation efforts form a control variable that influences the state variable x(t). The impact of w on soil erosion s(t) is given by: s(t) = s(w,t). We assume that $s_w \leq 0$, i.e., soil conservation efforts reduce erosion. Some methods require small initial investments of conservation efforts to control soil erosion effectively. Hence, such methods are likely to generate a convex soil erosion function, i.e., $s_{ww} \geq 0$. Methods that require high initial investment in conservation efforts are likely to show limited effectiveness at the beginning when farmers invest small amount of efforts in soil conservation. Such methods are likely to generate a soil erosion function that is concave, i.e., $s_{ww} \leq 0$. As shown in Fig. 1, soil conservation method 3 (w_3) has a convex s(w), w_2 a linear s(w), and w_1 a concave s(w) curve. Bench terraces are an example of a soil conservation method that may generate a concave soil erosion function. The bench terraces are usually constructed on lands with steep slopes and require high initial investment. Hence, a farmer who has just started construction of terraces will observe limited control of soil erosion. However, at higher investment, the bench terraces show considerable effectiveness (Barbier). Contours are constructed on less sloped lands. They are likely to generate a convex soil erosion function since they are easier to construct and hence require less initial conservation efforts.

The overall effect of s(w,t) on the dynamics of soil depth is captured by the equation of motion for x(t):

$$\dot{x} = k - s(w,t) \qquad (1)$$

where k is the natural regeneration of soil per year. For parsimony, k is assumed to be at a steady state constant. Soils in the tropics form naturally at a rate of 0.01 – 0.5 mm per year (Myers). Any other changes on natural soil regeneration that are induced by farm management are captured by the variable w.

In the case of soil quality, the endogenous variable is soil fertility management effort, a(t). Soil fertility management includes any practice that increases available nitrogen, n. Let the conversion factor of a(t) to n(t) be α such that, n(t) = αa(t).[1]

Mineralization, the natural process that converts organic matter into n, is assumed to contribute to n(t) constant amount of B per year. However, due to lack of synchrony between nitrogen availability and plant demand, Aune assumed that only half of B is actually taken up by plants. The nitrogen uptake by plants, m(t) is a function of nitrogenous fertilizer applied. Hence, equation of motion for available nitrogen is:

$$\dot{n} = \frac{B}{2} + aa - m(a) \qquad (2)$$

where m(a) is amount of nitrogen taken up by crops. It is assumed that a(t) increases n(t) but at the same time, the more fertilizer is applied, the more crops will take n, i.e.,

$$0 \le m_a \le \alpha \;\Rightarrow\; \alpha - m_a \ge 0 \qquad (3)$$

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[1] For example, urea fertilizer is 46% nitrogen. Let only 80% of applied urea be converted to available n. The remaining 20% of applied urea is assumed to be eroded, leached or volatized. Hence α = 0.46*0.8 = 0.37

The upper limit of m_a is α because increase in nitrogen uptake due to a unit increase in fertilizer application cannot exceed α. At higher levels of a(t), n(t) uptake tapers off, i.e., $m_{aa} \leq 0$.

Consider a farmer who maximizes profit subject to state variable constraints:

$$\underset{\{w,a\}}{\text{Max}}\ p = \int_0^T e^{-rt}\{py[x, n, t] - (c_1 w + c_2 a + z)\}dt + R[x(T), n(T)]e^{-rT} \qquad (4)$$

s.t.

$$\dot{x} = k - s(w)$$

$$\dot{n} = \frac{B}{2} + a\text{a} - m(a)$$

x(0) > 0, x(T) > 0, n(0) > 0, n(T) > 0, t(0) = t_0 and T given.

where r is the farmer's discount rate, p is crop price, y is crop yield per unit area, x is soil depth, n is the nitrogen available to plants at time t, c_1 is the cost of soil conservation efforts (w), a is nitrogenous fertilizer applied, c_2 is the unit price of nitrogen fertilizer, z is the total cost of inputs other than soil conservation efforts and nitrogenous fertilizer, R is the scrap value of land at the end of farmer's planning horizon, T. R is dependent on soil depth and nitrogen level at time T.

Suppressing the time argument, the current-value Hamiltonian and the associated first order necessary conditions are:

$$\tilde{H} = py[x, n] - (c_1 w + c_2 a + z) + l_1(t)[k - s(w)] + l_2(t)[\frac{B}{2} + a\text{a} - m(a)] \qquad (5)$$

$$\tilde{H}_w = -c_1 - s_w l_1 = 0 \ \Rightarrow l_1 = -\frac{c_1}{s_w} \qquad (6)$$

$$\tilde{H}_a = -c_2 + l_2(a - m_a) = 0 \Rightarrow \ l_2 = \frac{c_2}{a - m_a} \qquad (7)$$

$$\dot{l}_1 = rl_1 - \tilde{H}_x = rl_1 - p(y_x + y_n n_x) + l_2 n''(x)(k - s(w)) \qquad (8)$$

$$\dot{l}_2 = rl_2 - \tilde{H}_n = rl_2 - py_n$$

Transversality: $\lambda_1(T) = R_x e^{-rT}$, $\lambda_2(T) = R_n e^{-rT}$

Differentiating (6) with respect to t,

$$\dot{l}_1 = \frac{c_1 s_{ww}\,\dot{w}}{s_w^2} \;\Rightarrow\; \frac{c_1 s_{ww}\,\dot{w}}{} = r\,l_1 - py_x$$

We solve for $\dot{w}$ after eliminating λ_1.

$$\dot{w} = -\frac{s_w}{s_{ww}}\left[r + s_{ww}\,\frac{py_x}{c_1}\right] \tag{9}$$

which is the time path for the soil conservation effort. From (7),

$$\dot{l}_2 = \frac{c_2 m_{aa}\,\dot{a}}{(a - m_a)^2} \quad\Rightarrow\quad r\,l_2 - py_n = \frac{c_2 m_{aa}\,\dot{a}}{(a - m_a)^2} \tag{10}$$

Solving for $\dot{a}$ after eliminating λ_2,

$$\dot{a} = \frac{a - m_a}{m_{aa}}\left[r - \frac{py_n}{c_2}(a - m_a)\right] \tag{11}$$

which is the time path for fertilizer application. Omitting soil quality in the dynamic model looses the information in (11), which shows how soil nutrients behave over time.

Land Management and Improvement Policy Analysis

Policy analysts for land management and improvement are interested in identifying policy instruments that can be used to influence farmers to adopt soil conservation methods. Among instruments that may be considered are policies that affect output price, e.g. price support programs export subsidies, input subsidies, etc. There has been a debate among soil conservation economists as to whether price incentives increase or decrease soil degradation.

Schuh argued that price disincentives such as export taxes, high marketing costs, etc, influence farmers to undervalue land resource and hence degrade it much faster. Clarke observed that an increase in output price increases soil conservation efforts, which supports Schuh's conclusions.

Barbier, observed that price support programs increased soil erosion. Nielson and Lee, and LaFrance observed that farmers' response to productivity loss due to soil erosion is to apply more fertilizer and probably reduce soil conservation efforts. Lipton argued that higher output prices may encourage soil mining because farmers will plant crops that fetch higher prices but cause more severe soil erosion. Barret observed that output-pricing policies have little or no impact on soil conservation. Hence, he argued that alternative policies are required to influence farmers to adopt soil conservation methods.

The model developed in this research is used to analyze impacts of agricultural pricing policies on adoption of soil conservation technologies. The impact of output price on the control variables, w(t) and a(t) is analyzed at the steady state equilibrium. From (9) and (11),

$$rc_1 + py_x s_w = 0 \tag{12}$$

$$rc_1 - py_n(\alpha - m_a) = 0 \tag{13}$$

To analyze the impact of output price on soil conservation efforts, we conduct comparative statics analysis on (12) and (13) using the implicit function rule,

$$\frac{\partial w}{\partial p} = \frac{-s_w}{s_{ww}p} \begin{matrix} > 0 \\ < 0 \end{matrix} \quad \text{for} \quad \begin{matrix} s_{ww} > 0 \\ s_{ww} < 0 \end{matrix} \tag{14}$$

Unlike Clarke; LaFrance; Barbier; Lipton; and Barret, this research shows that the impact of output price on soil conservation efforts, s(w) depends on curvature of the s(w) function. For soil conservation methods with a convex s(w) curve, an increase in output price increases soil conservation efforts. The converse is true for methods that have concave s(w) curve.

For the available nitrogen case, (13) imply:

$$\frac{\partial a}{\partial p} = \frac{-(a - m_a)}{p m_{aa}} > 0 \qquad (15)$$

implying that an increase in output price leads to higher levels of fertilizer application. Unlike the soil conservation case, impact of output price on fertilizer application is not conditional, since, m(a) is assumed to be concave in a. These results further confirm the importance of explicitly specifying soil depth and soil quality in soil conservation models, as their response to different management practices may generate different functional relationships with state their variables.

Empirical Results and Discussion

This section discusses the empirical results of the transition dynamics of wheat production profitability, under soil degradation process, in northern Tanzania. Data for estimating wheat yield over time were simulated for more than 100 years. The Environmental Policy Integrated Climate, EPIC (Williams) was used to simulate crop yield. Data required for calibrating EPIC were collected from 185 farmers in 1998 and from a soil database at Selian Agricultural Research Institute, northern Tanzania. The actual and simulated yield were highly correlated, implying a high prediction power of EPIC. Actual and simulated wheat yield data ranged from 3 to 0.5 tons/ha. Input and output prices and other data required for computing farm profits were obtained from secondary sources. The wheat production profits over time were calculated using the simulated yield.

Two cases are considered in the analysis. One case involves wheat production profitability when both the soil erosion and fertility mining are considered in simulating wheat yield. This case reflects the production practices in northern Tanzania and other parts of SSA where soil mining and soil erosion are both serious problems. Yields for the soil erosion and fertility mining case were obtained by simulating the farming practice of growing wheat without applying any form of fertilizer and without controlling soil erosion. The second case allows the farmer to apply basal fertilizer to replenish soil nutrients taken up by crops. However, as for the case, the farmer is assumed not to control soil erosion. The application of 20 kg of phosphorus and 40 kg of nitrogen per hectare was simulated in the EPIC run for the (second) case that considers soil erosion only. The fertilizer rates are the recommendation for wheat production in northern Tanzania (Nyaki).

Figure 2 shows the transition dynamics of wheat production profit for the case considering both soil erosion and fertility mining and for the case accounting for soil erosion only. When we ignore fertility mining and hence assume that soil quality is constant, wheat simulated profits are much higher and hence, less realistic when compared to actual profits for farms that apply little or no fertilizer. For both cases, long-term wheat yields attain steady state equilibrium after 85 to 100 years. For the case that accounts for soil erosion only, the steady state average profit is Tanzanian Shillings (Tsh) 58,000/ha. For the case accounting for soil erosion and fertility mining, the corresponding profit is only Tsh 4,000/ha. However, farmers incur periods of losses before attaining the steady state equilibrium for the case that accounts for both soil erosion and fertility mining. These findings underscore the importance of including soil fertility mining in model specifications analyzing SSA soils.

Findings of this research have important implications for the feasibility of the transition path to the steady state equilibrium. Given the institutional environment in Tanzania, farmers do not have the incentives and ability to incur periods of negative profitability as a means of obtaining higher steady state net returns later since they are mainly subsistence producers. The implication of these findings is that government should support crop research programs to develop varieties suitable for the resource poor farmers. Research in organic fertilizers should also be supported to supplement the expensive inorganic fertilizers. Security of land tenure, whether through modern legal system or a traditional system is essential for soil conservation and improvement. Implementation of these policies is likely to reverse the current overexploitation of land resources in Northern Tanzania.

Conclusions

Soil erosion and fertility mining problems in Sub-Saharan African are important and hence call for models that explicitly address them. This research developed a model that shows the dynamics of both soil depth and available nitrogen. Empirical results indicate that where soil fertility mining is a serious problem, ignoring soil quality in modeling land degradation results in overestimating the transition dynamics and consequent steady state equilibrium of farm profits.

Comparative statics of the model show that the impact of output price on soil conservation efforts, w, depends on the curvature of the soil erosion function, s(w). A convex s(w) function implies that an increase in output price leads to an increase in soil conservation efforts. A concave s(w) function implies that an increase in output price decreases soil conservation efforts and hence more soil degradation. In the case of available nitrogen, an increase in output price increases the level of fertilizer application.

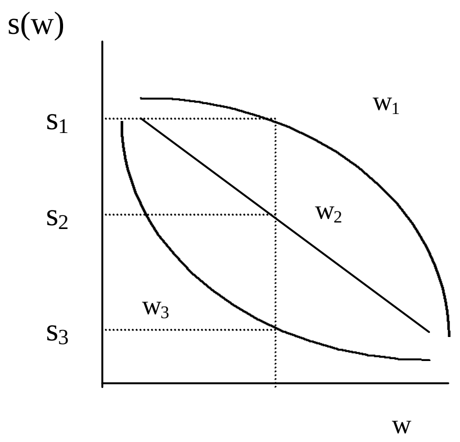
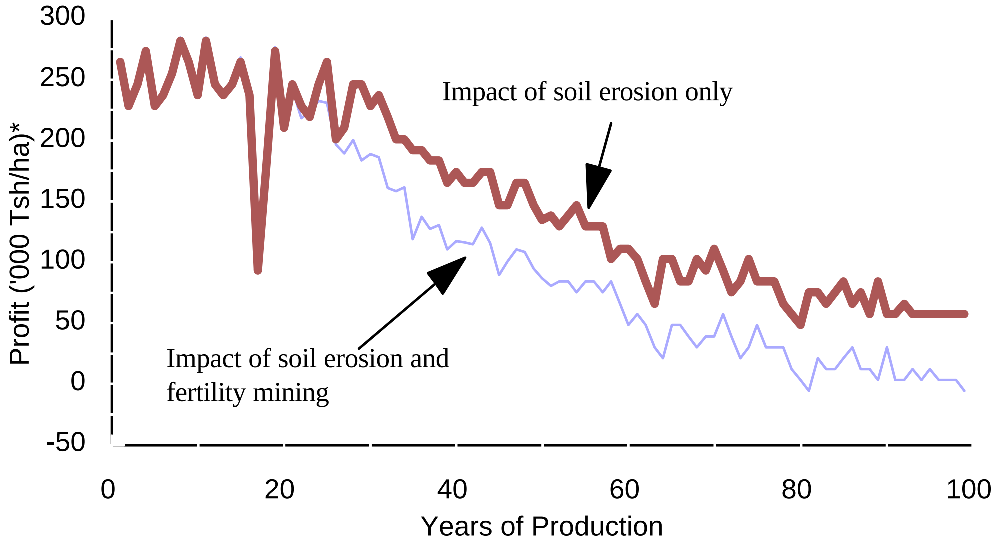


Fig. 1: Effect of soil conservation methods,
w efficiency on curvature of s(w).



* Tsh = Constant 1996/97 Tanzanian Shillings. Tsh 1 = 1996/97 US$632

Source: Yield data simulated using EPIC (Williams). Data to calibrate EPIC collected from farmers

Figure 2: Impact of Land Degradation on Wheat Production Profit,

Northern Tanzania

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ENVIRONMENTAL AND ECONOMIC IMPACTS OF SOIL EROSION AND FERTILITY MINING IN NORTHERN TANZANIA

ABSTRACT

This paper develops a soil conservation model that is relevant to smallholder farmers who apply little or no fertilizer. Empirical results drawn from northern Tanzania imply that, ignoring fertility mining problem in model specification leads to overestimation of profits for farms that apply little or no fertilizer. The model also shows that, the impact of output price on soil conservation efforts depends on the curvature of the soil erosion function.

Key words: Soil erosion, Fertility mining, Soil conservation, Price policy, Soil erosion function, Sub-Saharan Africa, Tanzania.