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RESTORING SOIL FERTILITY IN SUB-SAHARAN AFRICA: Technical and Economic Issues

By

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BACKGROUND: While recognizing the economic obstacles that currently block widespread use, many concerned with improving agricultural productivity and food security in Sub-Saharan Africa (SSA) are focusing on fertilizer[1] as a remedy for declining soil quality and stagnant yields. Some have suggested that SSA needs to increase fertilizer use from 9 to at least 30 kg/ha during the next decade. Others fear that increased use will have undesirable environmental impacts (soil acidification, water pollution) that could outweigh the benefits. The evidence -- both technical and economic -- underlying these arguments needs to be understood by those designing policies to promote agricultural productivity and to reverse declining trends in SSA soil quality.

OBJECTIVES AND METHODS: This synthesis focuses on three fertilizer issues: (1) the capacity of fertilizer, used with complementary organic inputs, to recapitalize SSA soils and improve productivity, (2) the economic obstacles and incentives to recapitalization, and (3) the need to guard against negative environmental impacts from fertilizer-led soil recapitalization.

Soil recapitalization is the replenishment of soil fertility as nutrients are added to the soil (inflows) to replace nutrients removed from the soil (outflows) by harvests, erosion, runoff, leaching, N volatilization, and denitrification. The reverse of recapitalization is soil mining, which occurs when nutrient outflows exceed inflows. Soil fertility is considered a form of renewable natural capital with service flows (crop production, food security) that increase with recapitalization and decrease with mining. The objective of recapitalization is not to build up maximum stocks of nutrient capital, but *appropriate* stocks of nutrient capital which can provide sustainable levels of nutrients to crops. Determining the *appropriate* level of stocks is a complex issue involving private and public goals for agricultural production and environmental quality, an analysis of both private and public costs and benefits, and a technical understanding of what is feasible.

The central argument presented here is that **SSA's decline in soil quality and agri-**

[1] In this document, 'fertilizer' means 'inorganic fertilizer.'

cultural productivity can be reversed through increased use of fertilizers, increased application of organic supplements (e.g., recycled crop residues or manure), and more attention to improving the technical and economic efficiency of fertilizer. Evidence in support of this argument is drawn from an extensive review of the literature on (1) soil mining, (2) recapitalization of degraded soils, and (3) fertilizer efficiency.

FINDINGS:

Soil Mining. Scientists agree that the introduction of agriculture results in declines of soil quality relative to the undisturbed system. Estimation of nutrient balances (inflows minus outflows) is a common method used to evaluate soil mining. Estimates for 38 countries in SSA suggest that annual loss of nutrients per hectare during the 1980s was 22 kg of N, 2.5 kg of P, and 15 kg of K.

Long-term soil mining can lead to loss of soil organic matter (SOM) with subsequent declines in nutrient-holding capacity, soil macro-structure, water-holding capacity and infiltration. For example, cultivation with low-input methods (no fertilizer) in the humid savanna zones of SSA can induce a 30% loss of SOM after 12 years and 66% after 46 years, with rice yields declining from 1 ton/ha to 300 kg/ha at the end of the period. Crop residues returned to the soil are not sufficient to offset these losses. The challenge is to halt soil mining and restore soil fertility before yields become so low that cropping activities are abandoned.

Technical Potential for Soil Recapitalization. The African landscape exhibits four broad types of soil, each with different responses to soil mining and recapitalization efforts:

Prime land contains highly buffered soils, high levels of SOM, and good water retention.[2] These soils (10% of the African land surface) exhibit little to no decline in SOM or fertility under various soil management systems.

High potential land contains predominantly well-buffered soils with some physical limitations. These soils (7% of land) are vulnerable to declines in SOM and fertility under low-input agriculture, but they have good potential for recapitalization (see below).

Low to medium potential land (28% of land) exhibits low to medium buffer capacity and is very vulnerable to declines in SOM and fertility under low-input agriculture. These soils can be recapitalized but often require management practices adapted to specific soil conditions.

Marginally sustainable land (57% of African total) has poorly buffered soils with very low SOM and very poor water retention. A large share is not arable (e.g., the Sahara Desert). The arable portions are on the fringes of deserts where both water availability and nutrients are limiting. The process of recapitalization for this group of *marginal* soils is not fully understood but some evidence suggests that it is possible.

Traditionally, **long fallows** were used to re-capitalize SSA soils and restore yields. Recent evidence suggests that fallows of 15-30 years are required to adequately recapitalize SSA soils. Population growth has put pressure on land so that such fallows are no longer feasible. Unfortunately, today's **short fallows** do little to restore SOM, hence alternative recapitalization techniques are needed.

[2] The buffering capacity of a soil is a measure of its ability to resist changes in pH; highly buffered soils are more resistant to acidification, which inhibits crop growth, than poorly buffered soils.

Fertilizer combined with recycled crop residues has good potential for recapitalizing high potential land. After 35 years of soil mining where 70% of SOM was lost, fertility was restored to Kansas prairie land in the 1950s through the introduction of fertilizer, which increased both yields and crop residues. The combined effect of fertilizer and the recycling of the crop residues resulted in 1-2% annual growth in SOM. The technical relationships observed in Kansas are likely to apply to high potential soils in SSA (and probably to medium/low potential land, but to a lesser degree). Unfortunately, the input/output price relationships prevailing in SSA do not provide the same incentives for fertilizer and residue use as those in Kansas during the 1950s.

Some aspects of recapitalization of marginally sustainable soils in SSA remain poorly understood. A study of the effect of crop residues, fertilizer, and manure on pearl millet production in Niger shows good yield response but no significant recapitalization or increase in SOM. To explain this lack of SOM response in *marginal* soils, soil scientists have hypothesized that there is a critical SOM level of 0.6% below which there is damage to soil structure resulting in irreversible erosion that precludes the possibility of SOM recapitalization. Another study, also from Niger, shows recapitalization in soils with SOM levels of 0.3% which is well below the hypothesized critical level for SOM.

A second issue is that organic matter is vulnerable to high rates of decomposition in marginal soils. Since the rate of decomposition is a major factor in determining the rate at which nutrients are released to the soil, a better understanding of the dynamics of organic matter in these soils could significantly enhance SSA's ability to increase yields and improve soil quality simultaneously.

Scientists agree that regardless of soil type, **sustainable recapitalization of SSA soils requires both fertilizer and organic amendments.** Fertilizer makes very little (if any) direct contribution to soil macro-structure, increased water-holding capacity, improved infiltration and erosion control, prevention of soil hardening or improved nutrient holding capacity. Organic matter alone will not work because there is not enough organic matter in SSA to recapitalize all the degraded soils under cultivation. Animal manures and plant material contain from 1 to 4% N while fertilizers contain from 20 to 46% N on a dry weight basis. The 100 kg N generally needed for a 4 t/ha maize crop, would require 217 kg of urea or 20,000 kg of leaf biomass! Furthermore, organic inputs are very low suppliers of P (the most critical limiting nutrient in Africa). Estimates range from 16 to 47 ha of grazing land that are required to produce sufficient manure for sustained maize production of 1 to 2 tons/ha in a semiarid West African environment. There is not sufficient manure to sustain even these moderate yields in many parts of West Africa.

Fertilizer can serve as a "catalyst" for SOM recapitalization if crop residues are returned to the soil. Fertilizer "primes the photosynthetic pump," helping the plant use more of the available carbon dioxide and water; the result is increased biomass production and yields. If the residual biomass (crop residue) is returned to the soil, there is an expected increase in SOM, which improves overall soil quality, stores organic nutrients, and helps protect against acidification and other side effects of fertilizer. When residues are removed, however, the higher grain and straw yields may actually remove more nutrients from the soil than were added (increased soil mining).

Crops and cropping patterns can be selected to increase crop residues and SOM. In general, maize produces abundant crop residues with a high carbon content. Legume crops have also been recommended, yet recent research suggests that monocropped maize is associated with higher levels of SOM than maize-soybean or other annual legume rotations. Maize rotations with perennial crops (small grains, forage grasses and legumes such as alfalfa) result in even higher levels of SOM. Choice of crop variety is also important, since for many crops, cultivars vary in their proportions of primary output (e.g., grain) and crop by-products (straw, leaves).

Increased recycling of crop residues depends on farmers' understanding of technical factors and on the costs and benefits of returning residues to the soil. Farmers may underestimate the nutrient content of crop residues, e.g., 74 kg of K from the straw produced on one hectare of millet yielding 1.2 tons of grain. Even when farmers understand the agronomic value of crop residues, the labor and machinery cost of incorporating them in the soil can be high. Another critical factor is that farmers commonly use crop residues for animal feed, fuel, or construction materials. Crops, cropping practices, and fertilizer doses must therefore be chosen to optimize the proportions of primary outputs and crop by-products given soil fertility and other household needs.

While increasing fertilizer use appears crucial for long-run soil recapitalization, two important issues must be addressed: the potential for negative side effects of fertilizer, and economic obstacles discouraging fertilizer adoption and the incorporation of crop residues.

Fertilizer's Negative Side Effects. Inappropriate fertilizer use can lead to productivity decline and environmental problems. There are two important problems associated with high levels of fertilizer used without complementary liming and/or organic amendments: acidification and losses in SOM due to increased soil mining.

Acidification or lowering of soil pH due to ammonium-N fertilizer use[3] increases the concentration of aluminum (Al) in the soil, which can severely affect crop growth. Crops such as sorghum suffer catastrophic yield declines at an Al saturation level of 30%. Other crops such as maize are more Al-tolerant. In general, the negative impacts of acidification depend on the buffering capacity of the soil. With highly buffered soils (uncommon in SSA), N fertilizer use has virtually no acidification and yield reduction effect. Under moderate conditions of buffering capacity and rainfall, yield may decline to zero over 15 to 20 years, or 25 to 30 years for Al-tolerant crops such as maize. Applying lime can reverse the acidification process in most situations.

Increasing fertilizer use can lead to environmental externalities such as water pollution. Although there is not yet evidence of large-scale water pollution from fertilizers in SSA, increasing fertilizer use could lead to N pollution of surface and ground water, with serious impacts on water quality and human health. Monitoring is needed to guard against such effects. Fertilizer application methods are also important. Proper application timing (*synchrony* strategies) can *tie up* N in microbial biomass at critical points in the crop growth cycle, thus maximizing efficiency of fertilizers and minimizing losses of polluting nutrients.

[3] N fertilizers, in order of their acid-forming capability, are ammonium sulfate = diammonium phosphate > monoammonium phosphate > anhydrous ammonia = urea = ammonium nitrate.

By allowing farmers to produce more on currently cultivated land, increased fertilizer use diminishes the need to clear forests in search of new land and benefits the environment to the extent that uncleared forests are the primary contributors to carbon sequestration and reduction of greenhouse gases. However, fertilizer used along with other technologies, e.g., mechanization, may have negative effects (soil erosion, leaching, or disruption of animal husbandry systems).

Economic Obstacles to Soil Recapitalization. The decision to recapitalize soils is generally a private one made by individual farmers on the basis of perceived financial returns. Farmers tend to focus on the short-run benefits of recommended technologies (e.g., the immediate returns to fertilizer), discounting the importance of long-term benefits from soil recapitalization, including long-term returns to fertilizer as well as those benefits that accrue to society in general, particularly future generations (e.g., more productive soils, improved food security, better air and water quality because forests have been saved, etc.). Given current input/output price ratios, the fertilizer investment required to "prime the recapitalization pump" is more expensive in SSA than elsewhere. Furthermore, agricultural credit systems in SSA seldom provide farmers with the liquidity needed to purchase desired amounts of fertilizer.

Government Actions to Improve Economic Incentives for Restoring Soil Fertility. Governments need to develop policies and make investments that will stimulate SSA farmers to undertake soil recapitalization. Although most industrialized nations have used some form of subsidy to encourage environmentally desirable production practices, there is much that can be done in SSA to increase fertilizer use without direct subsidies.

Governments can contribute to lower fertilizer costs by improving foreign exchange access, reducing direct and indirect taxes on fertilizer imports, investing in infrastructure that reduces transportation costs, and developing policies that promote greater efficiency in agricultural input and output markets. There is strong evidence that farmers who produce export (or other cash crops) are more likely to invest in fertilizer and other intensification technologies, hence policies that promote trade and the introduction of new cash crops can be important. Another way of reducing costs and increasing profitability is to encourage more efficient fertilizer use by farmers.

Fertilizer efficiency can be improved by fine-tuning recommendations and improving farmers' management techniques. In western agriculture, fertilizers are cheap and farmers have used blanket recommendations at high levels as "insurance." This encourages over-fertilization that results in non-point source pollution. Western scientists and farmers have learned that such recommendations are inefficient and wasteful. With the high cost of fertilizers in SSA, technically efficient use is critical. K, for example, is not considered a limiting factor in many African soils but the use of NPK complexes is common. Conversely, soils may have micronutrient deficiencies, such as sulphur or manganese, which are more limiting than K, yet these micronutrients are not included in commonly marketed fertilizers. While precision agriculture using high-tech equipment is not feasible, it is possible to take advantage of current knowledge, including climate data and national/regional soils information, to better develop and target fertilizer recommendations and improve the mix of products marketed. Extension services also need to improve their capacity to help farmers adapt recommendations to their particular situations, making use of farmers' knowledge of local soil conditions.

Recent efforts have improved the technical and economic efficiency of recommended fertilizer doses. Kenya recently developed trials to ascertain crop responses and profitability for various combinations of N, P and manure. Crop residues were routinely included in all sites. The results were used to develop fertilizer recommendations for previously delineated agroecological units, in an environment where minimal soil testing and extension expertise were available. A key feature of this project was simple, low-cost methods: it examined limited variables (N, P and manure), and existing data were used, rather than conducting an expensive soil survey.

Recent research has focused on how to improve the low profitability of fertilizer applied to particular crops and soils. Work on *marginal* soils in Burkina Faso and Niger has shown that it is possible to increase millet and sorghum yields profitably using fertilizer in combination with techniques that conserve and concentrate soil moisture and organic matter such as rock bunds and *zai* planting holes.

CONCLUSIONS:

- **Low-input agriculture in SSA has led to declining soil quality. External inputs will be needed to restore fertility.** The willingness of farmers to recapitalize their soils will depend on both technical feasibility and financial profitability.
- **Fertilizers and organic matter are complements rather than substitutes** -- both are required to recapitalize SSA soils.
- **Greater application of organic matter (crop residues, manure)** will require: (1) increased biomass production, (2) use of inorganic fuel sources and alternative construction materials, (4) better integration of livestock and crop production to improve manure supply, and (5) financial incentives for farmers to make soil recapitalization investments.
- **Increased fertilizer use** will require exploitation of cash-crop/fertilizer complementarities, fine-tuned and better-targeted recommendations, management practices that increase the technical and economic efficiency of fertilizer, and both reduction and stabilization of fertilizer costs.
- If fertilizer use increases significantly, **negative side effects will need to be monitored and incentives created for environmentally friendly fertilizer use.**

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