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REVIEW ARTICLE

Soil Nutrient Losses and Some Techniques for Improving Soils in Sub-Saharan Africa: A Review

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ABSTRACT

Soil nutrient depletion is quite severe in sub-Saharan Africa. More than 10 kg N, 4 kg P_2O_5 *and 10 kg* K_2O *per hectare per year are lost from the soil. Increased demand for agricultural commodities generated by an expanding population has resulted in intensification of cultivation and decreased periods of fallow. Fertility decline is inevitable with intensive, continuous cropping. A negative net nutrient balance for many cropping systems indicates the mining of nutrients from the soil and suggests that improved soil nutrient management practices may be needed to prevent the depletion of soil fertility. This paper reviews some of the causes of soil nutrient losses and the variety of soil-and water-management techniques necessary for achieving sustainable agricultural production.*

INTRODUCTION

Soil fertility replenishment, particularly in Sub-Saharan Africa (SSA), is increasingly viewed as critical to the process of poverty alleviation. This has been symbolized clearly by the award of the 2002 World Food Price to Pedro Sanchez, a pioneer in the field (Place *et al.*, 2003). Soil fertility is crucial because African poverty is mainly a rural phenomenon and per capita arable land in SSA has shrunk from 0.53 to 0.35 hectares between 1970 and 2000 (FAOSTAT, 2002).

African soils exhibit a variety of constraints: nutrient deficiency, soil loss from erosion, low organic matter, aluminium and iron toxicity, acidity, crusting, and moisture stress (Place *et al.*, 2003). Some of these constraints occur naturally in tropical soils, but degradation processes related to land management exacerbate them. Estimates suggest that nearly 80% of rangeland and dryland forest areas, 30% of tropical forests and around 50% of all irrigated cropland in developing countries are classified as degraded (Leonard *et al.,* 1989).

A major concern in traditional farming systems is the continuous and inexorable utilization of plant nutrients without replenishing nor compensating them through external inputs. The nutrient balance has been negative for most cropping systems in view of the fact that the amount of nutrients lost has been higher than that gained, indicating that farmers practise a farming system based on the exploitation of the soil's minerals. Stoorvogel and Smaling (1990) pointed out that in 1983, 49 kg/ha or an average of 9.3 million nutrients was lost in SSA, but that projections for the year 2000 showed that nutrient losses will increase to 60 kg per year, representing an expected loss of 13.2 million hectares of nutrients. In Nigeria, with a cropped land of 2813 million hectares, the nutrients losses were estimated at 1107605 tonnes of nitrogen, 316687 tonnes of P_2O_5 and 946157 tonnes of K_2O (Stoorvogel and Smaling, 1990).

This paper reviews some of the causes of soil nutrient losses and the available soil-and-water management techniques for improving soils and assuring sustainable agricultural production.

CAUSES OF SOIL NUTRIENT LOSSES

Weathering of soils: The long-term weathering of soil removes elements such as calcium, magnesium and potassium from the root zone and increases the hydrogen ion (H^+) concentration (Runge *et al.,* 1990). The result is a decreased soil pH or increased soil acidity (Pearson and Adams, 1967; Kamprath and Foy, 1971). In some soils, this condition increases availability of elements such as aluminium and manganese to levels that could be toxic to crop roots and in the process decrease their ability to use subsoil moisture (Runge *et al.,* 1990). Such soils cannot become productive until they receive applications of agricultural limestone to modify the soil chemistry (Runge *et al.,* 1990).

Burning of farm vegetation: Annual burning of fields and fallows during the dry season is common practice (Agboola, 1986). Burning helps to clear the land of weeds, bush growth and debris in order to facilitate cultivation. However, frequent burning of fields leads to physical and biochemical degradation of soils (Charreau, 1974). Burning usually causes nutrient losses through leaching, volatilization and surface runoff, destruction of soil organic matter and aggregate structure, and destruction of soil fauna and flora, thereby disrupting ecological equilibrium that existed prior to burning (Okigbo, 1985). Fire-burned soils are hydrophobic and become prone to excessive runoff and accelerated erosion (Lal and Okigbo, 1990). Ecological instability caused by repeated cycles of fire have resulted in denudation of vast areas of their protective vegetation cover, soil compaction, and unprecedented runoff and accelerated rates of erosion (Lal and Okigbo, 1990). Sometimes, standing economic trees and crops are unintentionally destroyed by fire and exposed to secondary infection by pests and pathogens (Okigbo, 1985). Soil fertility maintenance through bush fallowing has not also provided acceptable results because of annual burning of vegetation (Agboola, 1986). Similarly, although left-over ash retains nutrient cations and trace elements, these are not evenly distributed over the entire field (Agboola, 1986). The clearing and burning of vegetation and subsequent cropping also results in changes in the number and composition of soil fauna and flora (Nye and Greenland, 1960). Weed growth also increases where cultivation is continued without fallowing (Lal and Okigbo, 1990).

Land clearing and preparation: The farmer does both manual and mechanical clearing. Studies have, however, shown that in the tropics, soil fertility problems created by mechanical land clearing are greatest for soil fertility management (Agboola, 1986). Mechanized clearing, which is replacing manual clearing (and logging operations), causes scrapping away of rich top soil and compaction of subsoil which restricts water infiltration and root penetration and increases run-off and erosion (Lal and Okigbo, 1990). Land preparation via tractorization also seriously aggravates soil fertility degradation and is responsible for nutrient leaching, silting of rivers, soil wash, soil compaction, increased runoff, water and wind erosion, and clay pan formation (Agboola, 1986). Studies (Lal, 1981; Lal and Okigbo, 1990) have shown that: (i) runoff and erosion from mechanically-cleared lands are several orders of magnitude greater than those from traditional or manually-cleared land; and (ii) there are drastic reductions in fertility status of surface soil horizon of mechanically-cleared land in comparison with manual clearing or slash-and-burn traditional farming.

Low-input agriculture and inappropriate input application methods: Intensive farming without restorative fallowing or exogenous inputs is wasteful and degradative (Lal and Okigbo, 1990). Fertilizer use on traditional farms is still negligible, averaging 18 kg per ha of cropland (Barbier, 1998). Whereas average fertilizer usage is much higher in other developing regions of the world, and has increased since the early 1980s, the rate of application on Africa's cropland has hardly changed (Barbier, 1998). Reardon *et al.* (1990) point to low use of fertilizer across Africa as a major cause of concern, from both food-production and environmental perspectives. The authors particularly argue that the widespread "capital-deficient" unsustainable intensification in Africa is a major force behind farmland degradation and productivity loss. The limited use of nutrient inputs also exacerbates soil nutrient deficiency (Place *et al.*, 2003).

Broadcast applications, because of relatively low field operation costs, are the common practice for applying nitrogen fertilizer before planting. However, broadcasted nitrogen is more susceptible to loss to the environment than are banded applications, which place nitrogen fertilizer next to the plant (Taylor and Huang, 1994). For ammonia types of fertilizer, leaching and volatilization loss from broadcasting nitrogen on certain soils can be as much as 35 percent of nitrogen applied and can result in yield loss of as much as 15 percent (Achorn and

Broder, 1991; Meisinger and Randall, 1991; Mengel, 1986). In contrast, banded applications of anhydrous ammonia injected or knitted into the soil at or after planting can reduce nitrogen loss (Taylor and Huang, 1994).

Increased intensity of farming and shortening of fallow period: Increasing population pressure has resulted in decreased periods of fallow and intensification of agriculture (Lal and Okigbo, 1990). A survey by Goldman (1988) in Nigeria has indicated that during the last 20 years, fallow periods declined from 1 – 9 years to 0 – 6 years, a period much shorter than the 5 – 7 years required to restore soil fertility. Several studies have indicated drastic decline in soil fertility due to continuous cropping. One such study conducted at the research farm of the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria, showed rapid acidification, and reduction in organic carbon, total nitrogen, effective CEC, and exchangeable cations due to continuous cropping (Lal and Okigbo, 1990). Fertility depletion occurred despite addition of the recommended rates of fertilizers and return of residue as mulch (Lal and Okigbo, 1990). The depletion of bases resulting from continuous cultivation leads to a decrease in pH and an increase in exchangeable aluminium and hydrogen, with the rate of decline in pH more rapid in coarse-textured soils of low CEC and low organic carbon content than in heavy-textured soils of high buffer capacity (Lal and Okigbo, 1990). In addition to decline in soil chemical properties, continuous cropping also results in degradation of soil physical properties. A principal victim of continuous cropping, especially by mechanized means, is soil structure. Structural degradation is evident in rapid increase in bulk density, decrease in total and macro-porosity, reduction in infiltration capacity, and decrease in percent aggregation of soils (Lal and Okigbo, 1990).

Deforestation: When forests are unduly degraded or destroyed (whether through extensive logging or fuelwood gathering, or through clearing for agriculture), the loss amounts to far more than elimination of a source of wood. The productive capacity of the exposed soil is rapidly depleted through nutrient leaching, laterization and outright erosion (Myers, 1988). Thus, soil fertility in such formerly forested lands becomes markedly impaired or even irreversibly reduced. Another consequence of deforestation and depletion of fuelwood supplies is that it forces rural households to divert animal manure and crop residues from farm fields to house hearths (Myers, 1988). The present value of dung as fuel appear higher than its value as a soil nutrient. The context is one where there is no choice since there are neither fuel nor fertilizer substitutes to which households can gain access (Pearce, 1986). The result however is most certainly a decline in soil fertility, low levels of productivity, and loss of future economic welfare (Barbier, 1987). Deforestation also has both direct adverse effects on soil habitats and lowers faunal populations, and indirect effects through changes in microclimate, decreased food diversity, and exposure to predators and parasites (Lal and Okigbo, 1990).

Erosion: This is a selective process which removes the topmost fertile 0 – 5cm of soil and its ability to grow crops (Lal and Okigbo, 1990). One tonne of rich topsoil may contain as much as 4 kg of phosphorus, 10 kg of nitrogen, 66 kg of potassium, and 72 kg of calcium (Allison, 1973). Erosion specifically reduces water availability, removes nutrients (such as phosphorus, nitrogen, potassium, and calcium), reduces organic matter, and restricts rooting depth as the soil thins (Myers, 1988). As for the volume of soil lost, field findings range from just a few tonnes per year in flatish or carefully cultivated lands to 1000 tonnes or more in some exceptionally severe cases of steep slopes with friable soils (Myers, 1988). An average rate postulated by a World Bank survey of developing countries as a whole is 0.53 tonnes per ha per year (Sfeir-Younis, 1986).

Nutrient exports through harvests and crop residues: Harvested crops remove nutrients from the soil and unless these nutrients are replenished in adequate quantities, the natural resource base may be degraded through nutrient depletion and soil degradation (Bumb and Baanante, 1996). The crops grown also absorb nutrients from soil for growth and development and part of these nutrients are stored in the stover. Often, these nutrients are not returned to the field, given strong competition for crop residue between domestic uses (for fencing of fields and homesteads, roofing of homesteads, feeding of livestock, cooking and heating homes) and use for soil and water conservation practices or as a nutrient source (Agboola, 1986; Ofori, 1999). The complete removal of residues depletes soil of all nutrients, particularly cations (Agboola, 1986). In addition, organic matter content decreases drastically since organic matter affects both physical, chemical and biological properties of soils (Agboola, 1986). Crop wastes, if not processed through animals as feed or bedding to make them rot may even reduce nitrogen in the soil in the course of their decomposition. High nitrification losses of manure and organic residues occur in hot climates and reduce their fertilizer value (Oram *et al.,* 1979).

Leaching: Acidification as a chemical degradation process can occur when bases (such as calcium, magnesium, potassium, and sodium) are leached from the soil (Vesterby, 1994). Acidic soil conditions limit plant growth and reduce productivity because they supply insufficient calcium or magnesium, alter the decomposition rates of organic matter, and reduce the amount of nitrogen fixed by legumes (National Academy of Sciences, 1993).

Over-application of irrigation water: On sandy soils, such as those which dominate the plains in West Africa, little, if any, crop would be produced in some years without irrigation. The quantity of water in soil affects nutrient concentration in the soil and rate of nutrient movement to roots (Rhoads, 1991). Too much irrigation water can lead to substantial leaching of nitrogen, reduce nutrient concentration in soil and lower plant uptake (Taylor and Huang, 1994; Munson and Runge, 1990).

SOIL-AND WATER-MANAGEMENT TECHNIQUES FOR ENHANCING THE SOIL FOR CROP AND LIVESTOCK PRODUCTION

Improving soil conditions and making more water available are needed for increasing agricultural productivity. Some of the soil- and water- management practices for stimulating agricultural growth in a sustainable way include:

Natural fallow: This is the withdrawal of land from cultivation for a period of time to permit natural vegetation to grow on the plot (Place *et al.,* 2003). As long as fallow periods remain long and a low ratio of population to land area is maintained, the system is a sound soil conservation measure as the breaking of the crop cycle can lead to regeneration and the fallows can also recycle nutrients (Ruthernberg, 1971; Place *et al.,* 2003).

Improved, planted or managed fallow: This is the purposeful planting of a woody or herbaceous plant to grow on a plot for a period of time (Place *et al.,* 2003). In addition to benefits of natural fallows, improved fallows can achieve equal impacts of natural fallows in shorter time periods because of purposeful selection of plants, such as those that fix atmospheric nitrogen (Lal and Okigbo, 1990; Place *et al.,* 2003).

Chemical and organic fertilization: Chemical fertilizers increase both crop yields and biomass (living matter above and below the ground). Additional biomass can be used to augment the supply of organic matter (living and dead matter in soil), which helps in improving moisture retention, nutrient use efficiency and soil productivity (Bumb and Baanante, 1994). Chemical fertilizers are also useful in enhancing biological nitrogen fixation, as the nitrogen-fixing capacity of legumes is greatly influenced by availability of P and K in soil (through fertilizer application) and by soil pH (Bumb and Baanante, 1994). The spread of solid and liquid excrement from animals, mainly cattle (animal manure) and the collection, incubation, decomposition, and distribution of a range of organic compounds such as soil, animal waste, plant material, food wastes and even doses of mineral fertilizers (compost) are useful in: increasing micronutrient availability, improving soil organic matter, improving moisture-holding capacity and infiltration rates, lowering soil bulk densities (which affect the proportions of solids, air and water in soils), and improving microbial activity (Munson and Runge, 1990).

Conservation tillage: The preparation of land for planting (tillage) is a major operation each year (Galloway *et al.,* 1985; Moncrief *et al.,* 1988). By aerating soils and stimulating microbial activity, tillage enhances the mineralization of soil organic nitrogen, phosphorus and sulphur, and the decomposition of organic residues (Munson and Runge, 1990). Conservation tillage methods include no-till, ridge-till and mulch-till methods. In no-till, crop residues can decrease runoff and loss of herbicides or other chemicals to surface waters (Munson and Runge, 1990). Ridge-till systems for corn and soybeans grown in rotation have particular advantages because of the weed-control effects of ridging and the opportunity to band herbicides, as well as decreasing the need for insecticide to control corn rootworms (Munson and Runge, 1990). The maintenance of crop residue mulch on the soil surface also protects the soil against raindrop impact, prevents compaction of the soil thereby reducing run-off and erosion; supplies organic matter and nutrients to the soil, increases water infiltration rates, reduces the amplitude of temperature fluctuations, and increases yields (Lawes, 1966; Lal, 1976; Lal and Okigbo, 1990). A mulch should cover 70 – 75 percent of the soil surface to be effective (Quansah *et al.*, 1988). Increased microbial activity associated with crop residues also appears to increase herbicide or insecticide degradation and decrease leaching (Munson and Runge, 1990).

Cropping systems: These include mixed cropping, contour cropping, crop rotation and cover cropping. Mixed cropping systems make better use of soil resources as the root systems of component crops do not interfere with one another, exploit different soil layers (stratification of the root systems) and in combination, exploit a greater total volume of soil (Steiner, 1982; Willey, 1979). **Crop rotation** optimally exploits the soil resources by balancing crop nutrient demand with nutrient return by succeeding crops (Odunze, 1999). In contour strip cropping, crops are planted and rotated on the contour in alternate strips. This decreases movement of soil and water, and is particularly effective when combined with conservation tillage (Munson and Runge, 1990). **Cover crops** are planted for several purposes, such as reducing wind and water erosion, fixing nitrogen or decreasing the leaching of nutrients by recovering them in the crop for recycling (Munson and Runge, 1990).

Biomass transfer: This is the transport and application of green organic material from its *ex situ* site to the cropping area. The organic source may be purposefully or naturally grown (Place *et al.,* 2003).

Agroforestry: Planting trees in crop fields improves soil fertility through the nitrogen-fixing properties of the trees. The trees also provide shade and protect the soil from the scorching effects of the sun, provide a source of mulch, reduces erosion, recycles soil nutrients from the lower soil strata, and provide a source of firewood and animal forage (Jayne *et al.*, 1989).

Crop – livestock integration: The potential benefits of some degree of integration between crops and livestock have long been recognized in Sub-Saharan Africa. Crop-livestock integration provides farmers with an opportunity to diversify risk from single crop production; to use labour more efficiently; to have a source of cash for purchasing farm inputs; to add value to crops or their by-products; to maintain soil fertility by recycling nutrients and providing entry points for practices that promote sustainability such as the introduction of improved forage legumes; maintenance of soil biodiversity; minimize soil erosion; conserve water; provide suitable habitats for birds; and make the best use of crop residues that might otherwise be burnt leading to carbondioxide emissions (de Haan *et al*., 1997; Devendra and Thomas, 2002).

Mechanical conservation works: These include use of terraces, grassed waterways or buffer strips, and anti-erosion dikes and bunds. Terraces can be used on steep slopes to help hold water and soil sediment in the terrace channel, decreasing soil erosion and water runoff (Munson and Runge, 1990). Grass sod areas kept in place in areas that would otherwise experience serious soil erosion, and as buffer strips along ditches, ponds, lakes or rivers, help trap sediments and runoff into surface water (Munson and Runge, 1990). Dikes and bunds are barriers across runoff areas which are useful in increasing rainfall infiltration, limiting land degradation from soil erosion, and limiting the loss of manure and organic matter that would otherwise be washed-off from fields without runoff – control (Jayne *et al*., 1989).

Use of local agro-mineral resources: The use of locally-available agro-mineral resources is an important component of any integrated nutrient management approach in sub-Saharan Africa (Ofori, 1999). Perennial crops such as rubber and oil palm that are tolerant of acid soils and aluminium toxicity could benefit from the application of phosphate rocks (Ofori, 1999). In Malaysia, Othman and Sulaiman (1992) indicated that the application of phosphate rock to both leguminous cover and perennial crops is a widely used technique to overcome chemical constraints, particularly lack of P, in highly weathered upland soils. Rock phosphate can also be used to improve the quality of manure during storage; for example, additions of phosphate to manure reduces ammonia loss and thereby improves its fertilizer value (Ofori, 1999).

Water management: Highly variable rainfall in many parts of Sub-Saharan Africa makes water conservation vital, particularly in semi-arid areas and where dry spells are frequent (Cleaver and Schreiber, 1992). Effective water management is critical to reduce erosive and wasteful runoff and to maximize water infiltration into the soil. In most settings, in-situ water management through improved infiltration and moisture conservation is likely to be far less costly, more effective and less stressful for the environment than the construction of water-harvesting and storage structures. Some of the soil-improving techniques discussed above (such as intercropping and tillage) are extremely useful for *in-situ* moisture conservation, but under certain conditions (notably in low-rainfall areas), water-harvesting techniques may be both necessary and effective. Water harvesting is the collection and utilization of runoff for farming (or other uses) (Cleaver and Schreiber, 1992). A common form of water harvesting involves collecting runoff from a large area by means of earthen or stone bunds and guiding it through ditches or channels onto smaller areas where field crops are grown. Another common traditional technique is waterspreading: diverting runoff from seasonal streams or gullies to cultivated fields. By increasing the quantity of water available on cultivated land, these and other water-harvesting techniques greatly improve land productivity (Cleaver and Schreiber, 1992).

The productivity of farmland can also be improved in a manner consistent with resource conservation objectives through irrigation development. Only about 5 million hectares are irrigated in Sub-Saharan Africa, about half by modern means and the rest by traditional small-scale methods (Cleaver and Schreiber, 1992). The emphasis, however, should be on individually- or communally – managed irrigation systems, which can be developed and maintained by individual farmers themselves or by farmers' groups. Such low-cost schemes include irrigation from wells or pumps, controlled flooding and small-scale development of inland valleys and flood plains (Cleaver and Schreiber, 1992).

CONCLUSION:

Rapid soil nutrient depletion is a fundamental cause of soil degradation. This phenomenon is particularly evident on land under continuous cultivation where nutrient losses exceed nutrient replacement. Significant improvements in soil and water conditions at the farm level can promote productive and sustainable agricultural systems compatible with the intensification of land use that inevitably accompanies rapid population growth. The preference, however, should be for integrated soil fertility management approaches. For example, organic nutrient systems have been found to complement mineral fertilizers in many ways, both in a biophysical sense of enhancing soil health beyond nutrients alone and in a socio-economic sense of requiring different types of household resources (Place *et al.,* 2003). Crop rotations with cover crops can also capture nitrate in the soil and reduce nitrate leaching (Taylor and Huang, 1994). More stable agricultural returns is also more likely to enhance investment incentives. More appropriate nutrient management practices help farmers adjust fertilizer applications to crop needs and reduce losses to the environment. For example, soil and plant tissue tests help farmers estimate the residual nutrients available for plant use in determining fertilizer needs (Taylor and Huang, 1994). Timing nitrogen applications to the biological needs of a crop can reduce application rates in crop production by as much as 40 percent without reducing crop yield (Kanwar *et al*., 1988). Appropriate institutional and policy conditions are also needed to increase the adoption of soil-conserving technologies. Extension systems, for example, must be strengthened to increase farmer knowledge and understanding of new technological options. A more efficient rural financial system will assure improved access to credit for adoption of technologies requiring high cash outlays. Also, more secure land tenure arrangements will create an incentive for farmers to invest in soil-conserving techniques and practices.

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