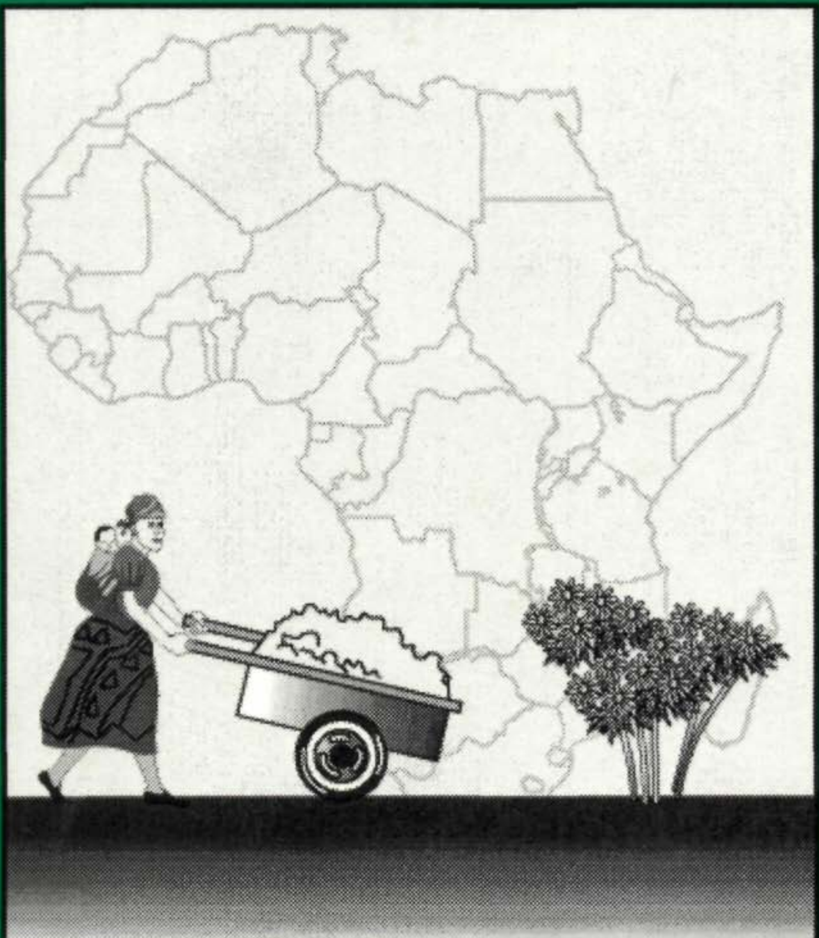
Replenishing Soil Fertility in Africa

SSSA Special Publication Number 51



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Replenishing Soil Fertility in Africa

Proceedings of an international symposium cosponsored by Divisions A-6 (International Agronomy) and S-4 (Soil Fertility and Plant Nutrition), and the International Center for Research in Agroforestry, held at the 88th Annual Meetings of the American Society of Agronomy and the Soil Science Society of America, Indianapolis, Indiana, 6 November 1996.

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FOREWORD

The 1996 World Food Summit highlighted sub-Saharan Africa as the remaining region in the world with decreasing food production per capita. The worst levels of poverty and malnutrition in the world exist in this region.

A team of scientists has identified declining soil fertility as the fundamental agronomic cause for declining food productivity in Africa. A "Soil Fertility Initiative for Africa" has been created by a group of international organizations including the World Bank, Food and Agriculture Organization (FAO), International Center for Research on Agroforestry (ICRAF), International Fertilizer Development Center (IFDC), International Fertilizer Association (IFA), and International Food Policy Research Institute (IFPRI).

This SSSA-ASA Special Publication is a comprehensive treatise that brings science to bear on current approaches to replenish soil fertility in Africa. It is the proceedings of an international symposium cosponsored by ASA Divisions A-6 (International Agronomy) and SSSA Division S-4 (Soil Fertility and Plant Nutrition), and ICRAF. The symposium was held on 6 November 1996 at the joint annual meeting of ASA and SSSA in Indianapolis Indiana.

This book is an excellent resource for anyone interested in the development of food supplies in Africa or problems of soil fertility anywhere in the world. Our Societies are proud to publish this pioneering work written by its members and by colleagues from other disciplines. It is an example of our Societies' contribution to addressing problems on a global scale.

D. Keith Cassel, President
Soil Science Society of America

William McFee, President
American Society of Agronomy

PREFACE

Sub-Saharan Africa is the last continent facing massive problems of food security because of decreasing per-capita food production. Extreme poverty (per capita incomes of <1 U.S. dollar per day), widespread malnutrition and massive environmental degradation are direct consequences of a policy environment that results in large scale nutrient mining. A series of awareness-raising events during the last 2 yr has brought the issue of soil fertility depletion in Africa to a similar level of importance as the issue of low-yielding rice and wheat varieties in Asia three decades ago, which triggered the Green Revolution that dramatically increased per capita food production in Asia and Latin America.

This SSSA Special Publication brings together the current thinking of a multidisciplinary team on soil scientists, agronomists, economists, anthropologists, and foresters as well as leaders of African national research institutes, international research centers, nongovernmental organizations, and universities in Africa, the USA and Europe. The 10 chapters are coauthored by a diverse group of 41 scientists from 14 countries, about one-half of the authors are currently working in Africa.

The first chapter presents the new conceptual approach of replenishing soil fertility as an investment in natural resource capital. It is followed by an analysis of the magnitude of soil fertility depletion (Smaling et al.), a review of field research trials (Bekunda et al.), an exciting NGO approach (Quinones et al.), and a perspective from temperate-region soils (Buol & Stokes). These in turn are followed by three process-oriented chapters on phosphorus (Buresh et al.), nitrogen (Giller et al.), and combining organic and inorganic nutrient inputs (Palm et al.). The last two focus on key socieconomic considerations, gender (Gladwin et al.) and environmental economics (Izac).

The editors wish to acknowledge the assistance of P.K. Nair and Tom Doerge, A-6 and S-4 Division Program chairs for assistance in organizing the symposium, to Paramu Mafongoya and Rob Bertram for chairing the sessions, the 200 partipants for lively discussions, the 25 peer reviewers for their critical input, and to Helen van Houten, Kellen Kebaara, and Fiona Chandler of ICRAF, and Marian Viney of ASA Headquarters staff for editorial assistance.

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Conversion Factors for SI and non-SI Units

To convert Column 1 into Column 2, multiply by	Column 1 SI Unit	Column 2 non-SI Units	To convert Column 2 into Column I, multiply by
		Length	
0.621	kilometer, km (10^3 m)	mile, mi	1.609
1.094	meter, m	yard, yd	0.914
3.28	meter, m	foot, ft	0.304
1.0	micrometer, um (10^6 m)	micron, u	**1.0**
3.94 x 10-^{2}	millimeter, mm (10^{-3} m)	inch, in	25.4
10	nanometer, nm (10~^{9} m)	Angstrom, A	0.1
		Area	
2.47	hectare, ha	acre	0.405
247	square kilometer, km^2 (10^3 $m)^2$	acre	4.05 x io-^{3}
0.386	square kilometer, km^2 (10^3 $m)^2$	square mile, mi^2	2.590
2.47 x 10-^{4}	square meter, m^2	acre	4.05 x io^3
10.76	square meter, m^2	square foot, ft^2	9.29 x 10"^{2}
1.55 x 10-^{3}	square millimeter, mm^2 (10^{-3} $m)^2$	square inch, in^2	645
		Volume	
9.73 x io-^{3}	cubic meter, m^3	acre-inch	102.8
35.3	cubic meter, m^3	cubic foot, ft^3	2.83 x io-^{2}
6.10 x io^4	cubic meter, m^3	cubicjnch,in^3	1.64 x 10"^{5}
2.84 x 10-^{2}	liter, L (10"^{3} m^3)	bushel/Blr	35.24
1.057	liter, L (IO"^{3} m^3)	quart (liquid), qt	0.946
3.53 x 10-^{2}	liter, L(10"^{3}m^3)	cubic foot, ft^3	28.3
0.265	liter, L (10~^{3} m^3)	gallon	3.78
33.78	liter, L (10"^{3} m^3)	ounce (fluid), oz	2.96 x 10"^{2}
2.11	liter, L (10"^{3} m^3)	pint (fluid), pt	0.473

Mass

2.20×10^{-3}	gram, g (10^{-3} kg)	pound, lb	454
3.52×10^{-2}	gram, g (10^{-3} kg)	ounce (avdp), oz	28.4
2.205	kilogram, kg	pound, lb	0.454
0.01	kilogram, kg	quintal (metric), q	100
1.10 x 10"3	kilogram, kg	ton (2000 lb), ton	907
1.102	megagram, Mg (tonne)	ton (U.S.), ton	0.907
1.102	tonne, t	ton (U.S.), ton	0.907

Yield and Rate

0.893	kilogram per hectare, kg ha^{-1}	pound per acre, lb $acre^{-1}$	1.12
7.77×10^{-2}	kilogram per cubic meter, kg m^{-3}	pound per bushel, lb bu^{-1}	12.87
1.49 x io-2	kilogram per hectare, kg ha^{-1}	bushel per acre, 60 lb	67.19
1.59×10^{-2}	kilogram per hectare, kg ha^{-1}	bushel per acre, 56 lb	62.71
1.86×10^{-2}	kilogram per hectare, kg ha^{-1}	bushel per acre, 48 lb	53.75
0.107	liter per hectare, L ha^{-1}	gallon per acre	9.35
893	tonnes per hectare, t ha^{-1}	pound per acre, lb acre-1[1]	1.12×10^{-3}
893	megagram per hectare, Mg ha^{-1}	pound per acre, lb $acre^{-1}$	1.12×10^{-3}
0.446	megagram per hectare, Mg ha^{-1}	ton (2000 lb) per acre, ton $acre^{-1}$	2.24
2.24	meter per second, m s^{-1}	mile per hour	0.447

Specific Surface

10	square meter per kilogram, m^2 kg^{-1}	square centimeter per gram, cm^2 g^{-1}	0.1
1000	square meter per kilogram, m^2 kg^{-1}	square millimeter per gram, mm^2 g^{-1}	0.001

Pressure

9.90	megapascal, MPa (10^6 Pa)	atmosphere	0.101
10	megapascal, MPa (10^6 Pa)	bar	0.1
1.00	megagram, per cubic meter, Mg m~3	gram per cubic centimeter, g cm"3	1.00
2.09×10^{-2}	pascal, **Pa**	pound per square foot, lb ft"2	47.9
1.45 x 10^	pascal, Pa	pound per square inch, lb in"2	6.90×10^3

(continued on next page)

Conversion Factors for SI and non-SI Units

To convert Column 1 into Column 2, multiply by	Column 1 SI Unit	Column 2 non-SI Units	To convert Column 2 into Column 1, multiply by
	Temperature		
1.00 (K-273)	Kelvin, K	Celsius, °C	1.00 (°C +273)
(9/5 °C) + 32	Celsius, °C	Fahrenheit, °F	5/9 (°F - 32)
	Enei **Vork, Quantity of Heat**		
9.52 x lO-^{4}	joule, J	British thermal unit, Btu	1.05 x 10^{3}
0.239	joule, J	calorie, cal	4.19
10^{7}	joule, J	erg	lO"^{7}
0.735	joule, J	foot-pound	1.36
2.387 x 10-^{5}	joule per square meter, J nr^{2}	calorie per square centimeter (langley)	4.19 x 10^{4}
10^{s}	newton, N	dyne	lO"^{5}
1.43 x 10^{-3}	watt per square meter, W nr^{2}	calorie per square centimeter minute (irradiance), cal cm"^{2} min"^{1}	698
	Transpiration and Photosynthesis		
3.60 x 10^{-2}	milligram per square meter second, mg nr^{2} s-^{1}	gram per square decimeter hour, g dm^{-2} h^{-1}	27.8
5.56 x 10-^{3}	milligram (H_20) per square meter second, mg nr^{2} s^{-1}	micromole (H_20) per square centimeter second, nmol cm^{-2} s-^{1}	180
10^{-4}	milligram per square meter second, mg m~^{2} s-^{1}	milligram per square centimeter second, mg cm^{-2} s-^{1}	10^{4}
35.97	milligram per square meter second, mg m^{-2} s^{-1}	milligram per square decimeter hour, mg dm-^{2} h-^{1}	2.78 x 10^{-2}
	Plane Angle		
57.3	radian, rad	degrees (angle), °	1.75 x 10"^{2}

Electrical Conductivity, Electricity, and Magnetism

10	siemen per meter, S m^{-1}	millimho per centimeter, mmho cm^{-1}	**0.1**
10^4	tesla, T	gauss, G	10^{-4}

Water Measurement

9.73×10^{-3}	cubic meter, m^3	acre-inches, acre-in	102.8
9.81×10^{-3}	cubic meter per hour, $m^3\ h^{-1}$	cubic feet per second, $ft^3\ s^{-1}$	101.9
4.40	cubic meter per hour, $m^3\ h^{-1}$	U.S. gallons per minute, gal min^{-1}	0.227
8.11	hectare-meters, ha-m	acre-feet, acre-ft	0.123
97.28	hectare-meters, ha-m	acre-inches, acre-in	1.03×10^{-2}
8.1×10^{-2}	hectare-centimeters, ha-cm	acre-feet, acre-ft	12.33

Concentrations

1	centimole per kilogram, cmol kg^{-1}	milliequivalents per 100 grams, meq 100 g^{-1}	1
0.1	gram per kilogram, g kg^{-1}	percent, %	10
1	milligram per kilogram, mg kg^{-1}	parts per million, ppm	1

Radioactivity

2.7×10^{-11}	becquerel, Bq	curie, Ci	3.7×10^{10}
2.7×10^{-2}	becquerel per kilogram, Bq kg^{-1}	picocurie per gram, pCi g^{-1}	37
100	gray, Gy (absorbed dose)	rad, rd	0.01
100	sievert, Sv (equivalent dose)	rem (roentgen equivalent man)	0.01

Plant Nutrient Conversion

	Elemental	*Oxide*	
2.29	P	P_2O_5	0.437
1.20	K	K_2O	0.830
1.39	Ca	CaO	0.715
1.66	Mg	MgO	0.602

24293

1 Soil Fertility Replenishment in Africa: An Investment in Natural Resource Capital

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ABSTRACT

Soil-fertility depletion in smallholder farms is the fundamental biophysical root cause for declining per capita food production in sub-Saharan Africa. An average of 660 kg N ha^{-1}, 75 kg P ha^{-1}, and 450 kg K ha^{-1} has been lost during the last 30 yr from about 200 million ha of cultivated land in 37 African countries. We propose an alternative approach, the replenishment of soil fertility as an investment in natural resource capital.

This approach combines basic principles of soil science with environmental economics. Combinations of P fertilizers and organic inputs can replenish soil N and P nutrient stocks in Africa and restore service flows to near original levels. Phosphorus replenishment strategies are mainly mineral-fertilizer based, with biological supplementation. Nitrogen replenishment strategies are mainly biologically based with mineral-fertilizer supplementation. Africa has ample phosphate rock (PR) deposits that can be either used directly or processed to reverse P depletion. Decomposing organic inputs may facilitate the use of PR in P-depleted soils. Leguminous tree fallows and herbaceous cover crops grown in situ play a major role in N capture and internal cycling in ways compatible with farmer constraints. Soil-fertility replenishment was found profitable in three case studies, but smallholder farmers lack the capital and access to credit to make the initial investment. A cost-shared initial capital investment to purchase P fertilizer and germplasm for growth of organic inputs combined with effective microcredit for recurring costs such as fertilizers and hybrid seed is seen as the way forward.

The continued threat to the world's land resources is exacerbated by the need to reduce poverty and unsustainable farming practices. During the last decade, food security was not a global priority, but studies such as the 2020 Vision (IFPRI, 1995, 1996) and the World Food Summit (FAO, 1996) have shown that food security is one of the main global concerns as we move into the next century. Food insecurity encompasses food scarcity as well as the inability to purchase food, a poverty-related issue. Although food insecurity occurs throughout the developing world, it is most acute in sub-Saharan Africa (hereafter referred to as Africa), where the attainment of food security is intrinsically linked with reversing agricultural stagnation, safeguarding the natural resource base, and reducing population growth rates (Cleaver & Schreiber, 1994).

In contrast to sustained increases in other parts of the developing world, per capita food production continues to decrease in Africa (Fig. 1-1; World Bank, 1996a). This is largely a result of continuing rapid population growth, the high-

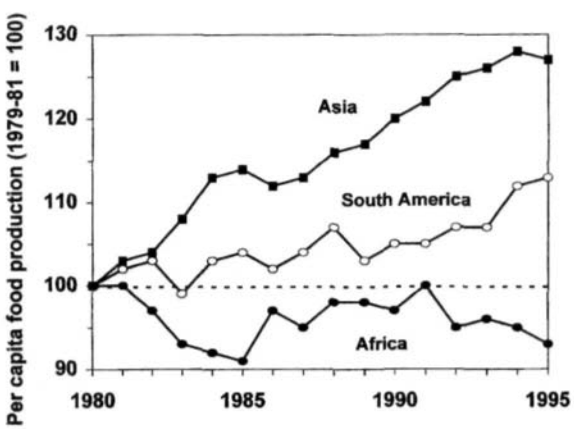

Fig. 1–1. Per capita food production in Africa lags behind that in Asia and Latin America (from World Bank 1996a,b).

est of any region in the world, and rapid land depletion (Badiane & Delgado, 1995; World Bank, 1995). In addition, about one-half of Africa's population is classified as absolute poor (those subsisting on per capita incomes of <1 U.S. dollar per day), and Africa has the highest proportion of undernourished children. To reverse this situation by the year 2020, Africa needs an annual, sustained growth rate in agricultural production of 4% (Badiane & Delgado, 1995).

Three requirements for increasing per capita agricultural production have been identified: (i) an enabling policy environment for the smallholder farming sector (improved road infrastructure, access to education, credit, inputs, markets, and extension services), (ii) reversing soil-fertility depletion, and (iii) intensifying and diversifying land use with high-value products (Sanchez & Leakey, 1997).

The purpose of this chapter is to propose a conceptual approach to increasing food security and poverty alleviation in Africa, *the replenishment of soil fertility as an investment in natural resource capital,* and to outline the elements of strategies for its implementation. This approach has been developed in response to a call by former World Bank President Lewis Preston for ideas on how to invest in natural resources in Africa (remarks to CGIAR Center Directors during International Centers' Week, 24 October 1994, Washington, DC).

For some time, the research community has recognized low soil fertility, particularly N and P deficiencies, as one of the major biophysical constraints affecting African agriculture (Nye & Greenland, 1960; FAO, 1971; DeWit, 1981, 1992; Penning de Vries & Djiteye, 1982; Mokwunye & Vlek, 1986; Pieri, 1989; Mokwunye, 1991; Yates & Kiss, 1992; Van der Pol, 1992; Aune, 1993; Smaling, 1993; Wang'ati & Kebaara, 1993; Mokwunye et al., 1996). However, soil fertility in Africa has seldom been considered a critical issue by the development community, who until very recently have focused primarily on other biophysical constraints such as soil erosion, droughts, and the need for improved crop germplasm (Lele, 1981; Eicher, 1982; Davis & Schirmer, 1987; World Bank, 1989, 1995; Anderson, 1994; Crosson & Anderson, 1995). Based on Smaling's (1993) nutrient balance studies and our own field observations across Africa, we have concluded that *soil-fertility depletion in smallholder farms is the fundamental biophysical root cause of declining per capita food production in Africa, and soil-fertility replenishment should be considered as an investment in natural resource capital* (Sanchez et al., 1996).

By fundamental root cause, we mean that no matter how effectively other conditions are remedied, per capita food production in Africa will continue to decrease unless soil-fertility depletion is effectively addressed. During in the 1960s, the fundamental root cause of declining per capita food production was the lack of short-statured, high-yielding varieties of rice *{Oryza sativa* L.) and wheat *(Triticum aestivum* L.) in Asia. Food security was only effectively addressed with the advent of improved germplasm in this region. Then other key aspects mat had been largely ineffective (irrigation, seed production, fertilizer use, pest management, research and extension services, and enabling government policies) came into play in support of the new varieties in Asia. The need for soil-fertility replenishment in Africa, therefore, is analogous to the need for Green Revolution-type germplasm in Asia three decades ago.

NUTRIENT DEPLETION

Magnitude of the Problem

The magnitude of nutrient depletion in Africa's agricultural land is enormous. Calculations from Smaling's seminal work (Stoorvogel & Smaling, 1990; Smaling 1993; Smaling et al., 1997, this publication) indicate that an average of 660 kg N ha^{-1}, 75 kg P ha^{-1}, and 450 kg K ha^{-1} has been lost during the last 30 yr from about 200 million ha of cultivated land in 37 African countries, excluding South Africa. This is equivalent to 1.4 t urea ha^{-1}, 375 kg triple superphosphate (TSP) ha^{-1} or 0.9 t PR of average composition ha^{-1}, and 896 kg KC1 ha^{-1} during the last three decades. These figures represent the balance between nutrient inputs as fertilizer, manure, atmospheric deposition, biological N_2 fixation (BNF), and sedimentation, and nutrient outputs as harvested products, crop-residue removals, leaching, gaseous losses, surface runoff, and erosion. These values are the aggregate of a wide variety of land-use systems, crops, and agroecological zones in each country (Stoorvogel & Smaling, 1990).

Africa is now losing 4.4 million t N, 0.5 million t P, and 3 million t K every year from its cultivated land. These rates are several times higher than Africa's annual fertilizer consumption, excluding South Africa—0.8 million t N, 0.26 million t P, and 0.2 million t K (FAO, 1995).

Commercial farms in the temperate region have averaged net positive nutrient balances in the order of 2000 kg N ha^{-1}, 700 kg P ha^{-1}, and 1000 kg K ha^{-1} during the last 30 yr in about 300 million ha of cultivated land, sometimes resulting in groundwater and stream pollution (Frissel, 1978, Sanchez, 1994). Nutrient depletion in Africa, therefore, contrasts sharply with nutrient accumulation in temperate regions.

Process

How has such gross depletion of soil nutrients come about in Africa? Everywhere in the world people settle first in high-potential areas with fertile soils, adequate rainfall, and mild temperatures (Sanchez & Buol, 1975), such as parts of the highlands of eastern and Central Africa, the plateau of southern Africa, and some river basins in West Africa. The Lake Victoria Basin in East Africa is one example, and now supports one of the densest rural populations in the world, 500 to 1200 inhabitants km^{-2} (Hoekstra & Corbett, 1995).

Such settlements were first supported by the originally high soil fertility. As populations grew, this fertility was gradually depleted by crop-harvest removals, leaching, and soil erosion, when farmers were unable to sufficiently compensate these losses by returning nutrients to tire soil via crop residues, manures, and mineral fertilizers (Shepherd & Soule, 1998).

Smallholder farmers also cultivate low-potential areas primarily in subhumid and semiarid areas, where many of the sandy soils are naturally infertile. Still, the smaller soil nutrient stock is also being depleted in these areas (Pieri, 1989; Smaling, 1993; Sanders et al., 1996).

Two overarching reasons for the nutrient depletion process are (i) the breakdown of traditional practices and (ii) the low priority given to the rural sector. Increasing pressures on agricultural land have resulted in much higher nutrient outflows and the subsequent breakdown of many traditional soil-fertility maintenance strategies, such as fallowing land, intercropping cereals with legume crops, mixed crop-livestock farming, and opening new lands. Such strategies have not been replaced by an effective fertilizer supply and distribution system (Sanders et al., 1996). Traditional African coping strategies were not capable of adjusting quickly enough to rapid population growth combined with decreasing farm size, soil fertility, and fuelwood availability (Cleaver & Schreiber, 1994). Nevertheless, African farmers repeatedly outperform the weather; current crop yields over time fluctuate considerably less than indices of rainfall (Dommen, 1988). Continued population pressure has reduced farm sizes to the point where farms can only provide adequate living for their families if the land is farmed very intensively and if there is off-farm income.

Most African governments have used agriculture as a main source of revenue by restricting producer prices and taxing exports (Cleaver, 1993). Relatively little attention has been paid to rural areas by national governments, lowering the relative returns to farming. Therefore, few improved soil-fertility management technologies have been widely accepted by African smallholder farmers (Conway & Barbier, 1990). The low national priority given to the rural sector in Africa also results in poor road and market infrastructure, lack of timely access to credit and inputs at reasonable cost, lack of timely information, and ineffective extension systems (Badiane & Delgado, 1995; Tomich et al., 1995). Soil-fertility depletion, therefore is largely a consequence of socioeconomic constraints and policy distortions.

Because the soil resource has not kept its productive capability over time, farmers have witnessed low and declining yields. Current crop yields are low due to poor agronomic practices, droughts, weed and pest attacks, lack of cash for investment, and soil-fertility depletion. Several decades of nutrient depletion have transformed originally fertile lands that yielded 2 to 4 t ha^{-1} of cereal grain, into infertile ones where cereal crops yields of <1 t ha^{-1} are common. For example, a long-term trial in Kabete, Kenya, indicates that a fertile, red soil (Oxic Rhodudalf) lost about 1 t ha^{-1} of soil organic N and 100 kg P ha^{-1} of soil organic P during 18 yr of continuous maize *(Zea mays* L.)-common bean *(Phaseolus vulgaris* L.) rotation in the absence of nutrient inputs. Maize yields without N and P fertilizer inputs decreased from 3 to 11 ha^{-1} during that period (Qureshi, 1991; Swift et al., 1994; Kapkiyai, 1996; Bekunda et al., 1997, this publication).

Nutrient depletion rates are field specific, depending on the way each particular field has been managed over decades. This results in a mosaic of degrees of nutrient mining at the landscape scale. At the national scale, there are areas that have not suffered much from nutrient depletion, because of the low intensity of use or the use of fertilizer for export crops. Still, nutrient-depleted, smallholder farms in Africa are much more common that ones where this constraint is not a major problem.

Nutrient depletion rates vary with soil properties. The proportion of nutrients lost is normally greater in sandy soils, but the total nutrient loss is greater in clayey soils. This is largely because soil organic matter (SOM) particles are less protected from microbial decomposition in sandier soils than in loamy or clayey ones (Sanchez, 1976; Pieri, 1989; Swift et al., 1994). This is one major difference between the nutrient-depleted, high-potential areas of East and southern Africa with predominantly loamy and clayey soils, and semiarid areas of West, East, and southern Africa with predominantly sandy soils.

The end result is mat soils have deteriorated significantly, especially in terms of P levels and SOM. It now requires a major investment to restore soils to a sufficient level of fertility for sustainable crop production.

Consequences of Nutrient Depletion

On-Farm Effects

A marked decline in crop productivity and food security are the main consequences of the policies that result in soil-fertility depletion in Africa. Nutrient depletion per se also produces negative on-farm side effects and exacerbates several off-farm effects or externalities. On-farm effects include less fodder for cattle, less fuelwood for cooking, and less crop residues and cattle manure to recycle nutrients. These effects often increase runoff and erosion losses because there is less plant cover to protect the soils. In sandy soils, the topsoil structure may collapse resulting in soil compaction or surface sealing.

Economic and Social Externalities

The negative effects of soil nutrient depletion extend beyond farming households into the community, regional, and national scales. Soil nutrient depletion lowers the returns to agricultural investment, which reduces nonfarm incomes at the community level through multiplier effects (Delgado et al., 1994). Other consequences of depletion are decreased food security through lower production and resulting higher food prices, increased government expenditures on health, more famine relief, and reduced government revenue due to less taxes collected on agricultural goods.

Perhaps the most important negative social externality of soil-fertility depletion is its link to lower employment and increased poverty. The vast majority of the poor live in rural areas in the tropics (World Bank, 1990). As long as returns to agriculture are limited by nutrient depletion, farm employment and spillover nonfarm employment opportunities will remain low, sustaining severe poverty. But these externalities are not confined to rural communities, as poverty often pushes individuals and households into urban areas. The influx of rural migrants puts a greater strain on the limited urban infrastructure; and unemployment, crime, and political unrest sometimes result (Homer-Dixon et al., 1993). This situation is typical in high-potential areas of eastern and southern Africa—particularly in Burundi, Ethiopia, Kenya, Malawi, Rwanda, Tanzania, Uganda, and Zambia as well as in low- and high-potential areas of West Africa.

Environmental Externalities

Soil-fertility depletion also exacerbates several environmental problems at the national and global scales. Increased soil erosion, particularly in steep areas, causes more unwanted sedimentation, siltation of reservoirs and of coastal areas, and in some cases eutrophication of rivers and lakes. There is evidence of these processes occurring in some African rivers and lakes (Melack & Maclntyre, 1992), including Lake Victoria, where erosion from surrounding nutrient-depleted lands is widespread.

The loss of topsoil organic C associated with soil nutrient depletion results in additional CO_2 emissions to the atmosphere from decreasing soil and plant C stocks. Assuming a C/N ratio of 10:1 in SOM, the average N depletion rate of 22 kg N ha^{-1} yr^{-1} represents an average rate of C loss of 220 kg C ha^{-1} yr^{-1} from 200 million ha of cultivated soils of Africa. Assuming that 40% of the losses are due to erosion (Smaling, 1993) and that C in sediments resulting from erosion is not lost to the atmosphere as CO_2, 27 Tg (10^{12} g) of C are annually emitted to the atmosphere from cultivated land in Africa. This amounts to about 21% of the 130 Tg C annually emitted from land degradation (Lai et al., 1995).

Carbon loss is a reversible process in soils as long as their clay contents are not decreased by erosion. Equilibrium soil organic C content is determined by soil temperature, moisture, clay content, and the balance between C input and decomposition rates (Nye & Greenland, 1960; Sanchez, 1976). It has been possible to increase organic C to their original levels by sound fertilizer and residue management practices in the temperate regions (Buol et al., 1990; Buol & Stokes, 1997, this publication). This C sequestration process is gradual (Giller et al., 1997, this publication) and definitely not instantaneous. Although it takes place primarily in the topsoil, it also can occur in the subsoil when deep-rooted grasses and trees are introduced in degraded lands (Fisher et al., 1994; Sanchez, 1995). The cry for increasing SOM in sandy soils, so often heard in West Africa, can only occur in nutrient-depleted soils, but never up to the levels found in high-potential clayey soils. With these caveats in mind, decreased CO_2 emissions and increased C sequestration can be a positive environmental externality of replenishing soil fertility.

Soil-fertility depletion decreases above- and belowground biodiversity and increases the encroachment of forests and woodlands in response to the need to clear additional land (Sanchez, 1995). This is particularly relevant to the Miombo woodlands of southern Africa and to the rainforest remnants in the Great Lakes region and in eastern Madagascar, both of which harbor unique animal biodiversity.

NEED FOR A NEW APPROACH

Existing Approaches

Traditional approaches for soil-fertility management range from recurring fertilizer applications to low external input agriculture based on organic sources of nutrients. Although both extremes work well in specific circumstances, they pose major limitations for most smallholder farmers in Africa.

Recurring Fertilizer Applications

Fertilizer use is the obvious way to overcome soil-fertility depletion, and indeed it has been responsible for a large part of the sustained increases in per capita food production that have occurred in Asia, Latin America, and the temperate region, as well as in the commercial farm sector in Africa (Mokwunye & Vlek, 1986; Mokwunye & Hammond, 1992; Borlaug & Dowswell, 1994; Buol & Stokes, 1997, this publication). There is nothing wrong, biophysically or environmentally, with fertilizers when properly used. Fertilizers provide the same nutrients as organic sources to plants. Plants cannot distinguish nitrate or phosphate ions they absorb from organic inputs from those they absorb from mineral fertilizers (hereafter referred to as inorganic fertilizers).

Most smallholder farmers in Africa appreciate the value of fertilizers, but they are seldom able to apply them at the recommended rates and at the appropriate time because of high cost, lack of credit, delivery delays, and low and variable returns (Badiane & Delgado, 1995; Runge-Metzger, 1995; Heisey & Mwangi, 1996; Larson & Frisvold, 1996). Such constraints are largely due to the lack of an enabling policy environment in rural areas caused by the deficient road and market infrastructure typical in most African countries.

The price of fertilizers in rural areas of Africa is usually at least twice the international price (Bumb & Baanante, 1996). Transport costs are about seven times higher in Africa than in the USA (U.S. dollars in t km^{-1}). Transport and other costs (import duties, demurrage, taxes) more than double the international price by the time fertilizers reach the farmer in Malawi (Donovan, 1996). This occurs in spite that during the past 25 yr the real international price of fertilizers has decreased by about 38% for N and >50% for P (Donovan, 1996).

In the past, many African countries subsidized fertilizers, however, the removal of fertilizer subsidies by most African governments as part of the Structural Adjustment Programs in the last decade has tripled or quadrupled fertilizer prices in relation to crop prices in many African countries (Holden & Shanmugarathan, 1994; Bumb & Baanante, 1996). Furthermore, since fertilizer recommendations are normally formulated to cover broad areas with diverse soils, farmers also lack information about the best fertilizer to use for their particular fields and cropping practices, making the crop response to fertilizers more erratic and less profitable.

These policy and information constraints can certainly be overcome, thereby in the longer term resulting in increased food security and reducing poverty. An excellent example of a promising approach is the Sasakawa Global 2000 project in Ethiopia, where many policy distortions have been overcome (Quinones et al., 1997, this publication).

Organic Farming

The exclusive use of organic inputs as external nutrient sources has been advocated as a logical alternative to expensive fertilizers in Africa (Reijntjes et al., 1992). The main advantages of this approach are (i) the replacement of scarce or nonexistent capital for labor and (ii) the fact that cattle manures or green manures contain all essential nutrients plus C, the source of energy for soil biota that regulates nutrient cycling.

One of the main arguments against the use of organic inputs is their low nutrient concentration in comparison with inorganic fertilizers. Animal manures and plant material contain from 1 to 4% N (10-40 g N kg^{-1}) on a dry weight basis, while inorganic fertilizers contain from 20 to 46% N (200—460 g N kg^{-1}) and are already dry. To haul the 100 kg N generally needed for a 4 t ha^{-1} maize crop, it would take 217 kg of urea or 201 of leaf biomass with 80% moisture and a 2.5% (25 g N kg^{-1}) N concentration on a dry weight basis. Furthermore, organic inputs are very low suppliers of P because of their low concentrations (Palm, 1995; Palm et al., 1997b, this publication).

It takes soil fertility to grow organic inputs, be they green manures, litterfall, plant biomass for transfer, composts, or animal manures. In nutrient-depleted soils it is difficult to grow enough forage to feed cattle and produce sufficient quantities of manure. The nutrient content of manures varies widely with soils and fodder availability in Africa (Murwira et al., 1995; Probert et al., 1995).

It is important to distinguish between nutrient inputs and nutrient cycling (Sanchez & Palm, 1996). At the field scale, nutrient inputs are additions from outside the system, such as N_2 fixed from the air by legumes or inorganic fertilizers. Cattle manures are inputs if the manure was produced from forage grown outside the field.

Nutrient cycling refers to the transfer of nutrients already in the field from one component to another, for example (i) the return of maize stover back to the soil, (ii) cattle manure and urine deposited by animals while grazing crop residues, and (iii) the transfer of nutrients from trees to the soil through prunnings, leaf drop, or root decomposition in agroforestry systems. Nutrient cycling is extremely important, but nutrient-depleted soils need inputs from outside the field.

African farmers, in our view, do not need low-input, low-output systems that do not address poverty alleviation. Given the limitations of the extremes of either pure organic inputs or pure inorganic inputs, the authors feel it is time for a more robust approach that provides fresh alternatives and increases the basket of options available to farmers and policy makers.

Natural Resource Capital

Capital, or the basis of value, may be divided into four general categories: natural, manufactured, human, and social capital (Serageldin, 1995). Natural capital is the stock of environmentally provided assets, such as the atmosphere, soil, water, forests, fish, wildlife, and wetlands. Manufactured capital is the capital people usually consider in financial and economic terms (e.g., money, houses, roads, factories, and vehicles). Human capital represents the education, health, and nutrition of individuals, while social capital reflects the institutional and cultural basis from which a society functions. The flow of goods and services from natural capital can be renewable or nonrenewable, and marketed or nonmarketed (Serageldin, 1995).

In the past, natural capital and its decline has seldom been taken into account. Now that human expansion has made large claims on the environment, natural capital has become an important limiting factor to economic development. For example, the loss of forests or fish populations has a greater impact on the possibilities for long-term, sustainable economic development than the loss of manufactured capital such as sawmills or fishing boats (Serageldin, 1995).

The current situation of depleted natural capital in many countries reflects decades of natural capital extraction in an attempt to build up other types of capital. Such a strategy was intended to lead to demand-driven investments across all types of capital and ultimately to sustainable growth; however, investments in natural resources remain low in most African countries. In many of them, natural resource capital values have depreciated to extremely low levels.

In the longer term, sustainable growth and poverty alleviation will depend on investment in and improvement of all four types of capital. There is an urgent need to reexamine past strategies and consider investments in natural capital as a means to achieving this goal. In the impoverished rural areas of Africa, encouraging investment in land resources may not only have the greatest impact on poverty alleviation in the short-term, but it may act as a catalyst for broader-based capital investment and growth in the long term. The remainder of this chapter focuses on the potential for investing in one type of natural resource capital—soil nutrients.

Nutrient Capital

Soil fertility is an important form of renewable natural capital. Plant nutrients in the soil, however, are among the least resilient components of sustainability (Fresco & Kroonenberg, 1992). The maintenance of soil fertility involves the return to the soil of the nutrients removed from it by harvests, runoff, erosion, leaching, and other loss pathways (Aune, 1993).

The soil nutrient capital of Africa is being mined, just like mineral deposits of metals or fossil fuels. As long as poverty and population pressure hinder farmers from replenishing this lost capital, the service flows emanating from nutrient capital will inevitably decrease. These service flows include on-farm soil fertility and crop production *(valued by individual farmers),* food security and soil conservation *(valued by national societies and farmers),* poverty alleviation, enhanced C sequestration, and biodiversity conservation *(valued by the global society and future generations).*

At the farm scale, it makes sense for farmers to reverse the mining of their nutrient capital up to the point where the marginal costs of nutrient replenishment are covered by the marginal benefits. For annual fertilizer applications, this means that the value of increased production brought about by the fertilizer should be sufficiently high to cover costs of the fertilizer, compensate for risk, and provide a reasonable return to the farmer.

Fertilizer application by smallholder farmers to food crops is often not profitable due to the combination of high fertilizer prices discussed earlier, low prices for food crops, and high risk. Even when fertilizer applications are profitable, many farmers cannot afford to purchase fertilizer at the beginning of the season when other, more basic needs, are pressing. Functioning credit markets could alleviate this constraint, but they have been difficult to develop for small farmers growing food crops in Africa due to the risky nature of rainfed agriculture, the lack of collateral, and the high cost of administering small loans to many smallholder farmers. On the other hand, fertilizers are often applied to cash crops such as coffee *(Cqffea* sp.) and tea *[Camellia sinensis* (L.) Kuntze] where the returns to fertilization are high and credit is available through cooperatives.

Nutrient Capital Defined

Nutrient capital can be defined as the stocks of N, P, and other essential elements in the soil that become available to plants during a time scale of 5 to 10 yr (Sanchez & Palm, 1996). The two most widespread limiting nutrients to food production in Africa are N and P, in that order (Ssali et al., 1986; Woomer & Muchena, 1996; Bekunda et al., 1997, this publication). For example, in a series of fertilizer trials conducted throughout the Kenyan highlands, N and P deficiencies were reported in 57 and 26% of the cases, respectively (Kenya Agricultural Research Institute, 1994). Potassium, Ca, Mg, S, and micronutrient deficiencies and Al toxicity do occur in specific circumstances in Africa, but not to the extent of N and P deficiencies. Potassium depletion rates (15 kg K ha^{-1} yr^{-1}) are six times that of P (Smaling et al., 1997, this publication), but crop responses to K fertilization are rare in Africa, except in sandy savanna soils (Ssali et al., 1986). This is probably due to the high K capital in many other parts of Africa and the low demands for K due to the current low crop yield levels. Consequently, in this chapter we focus on the two main limiting nutrients.

We propose to define N capital as the labile pools of soil organic N that seem to be well correlated with N release rates, such as particulate organic N (Kapkiyai, 1996), and N in the light fraction of SOM (Barrios et al., 1996). We also propose that P capital be defined as the labile pools of soil organic P (such as particulate organic P) together with sorbed or fixed P on Fe and Al oxides and hydroxides at the surface of layer-silicate clay particles. Nutrient capital may be expressed as kilograms per hectare of N or P within the rooting depth of plants. Precise methodologies, however, need to be developed.

Capital Stocks and Service Flows

There is an exact congruence between the concepts of capital stocks and service flows in economics and that of nutrient pools and fluxes in soil science (J.K. Lynam, 1997, personal communication). The above-defined nutrient capital stocks as discrete pools fit well with economic concepts. Nutrient fluxes during the growing period are synonymous to service flows. Such fluxes subtract from the nutrient capital and are thus analogous to the concept of depreciation.

Our goal is not to maximize nutrient stocks in the soil but rather to determine the minimal size of the nutrient stock that will maximize service flows, or the value of crop production for several years. An important question for P replenishment is whether service flows will be maximized with a one-time application of P or by gradually increasing the P stock through annual applications. In the case of P-depleted, high P-sorbing soils, small annual fertilizer P applications will go primarily to slowly available pools, making little P available to plants, therefore minimizing service flows. This calls for a strategy to rapidly replenish capital P pools, rather than less efficient, gradual build ups. Key advantages of rapid P replenishment are economies of scale and cost savings in delivering and applying P, particularly PR. The downsides are lack of credit and capital by farmers and the discount rate. As the discount rate increases, higher service flows from the investment are required to pay for the investment. In the case of N, however, the size of the capital N stocks cannot be built instantaneously like P capital stocks, so gradual build ups are needed. The critical factor is not the size of the N capital stocks, but the cycling rate (Giller et al., 1997, this publication).

Nitrogen and P, therefore, behave differently in terms of their replenishment strategies. We will tackle P replenishment first, because although less geographically widespread, it is the most critical of the two.

PHOSPHORUS REPLENISHMENT

Phosphorus deficiency is widely considered the main biophysical constraint to food production in large areas of farmland in subhumid and semiarid Africa (Penning de Vries & Djiteye, 1982; Ssali et al., 1986; Bationo et al., 1986, 1996). Phosphorus dynamics in soils are complex, because they involve both chemical and biological processes and the long-term effects of sorption (fixation) and desorption (release) processes. The low concentration and low solubility of P in soils frequently make P a limiting factor. The main features of the P cycle are shown in Fig. 1-2. The following section highlights the concepts and processes involved.

Inputs

Phosphorus inputs to farmer fields in Africa consist primarily of inorganic fertilizers and organic sources such as biomass, manures, and composts gathered

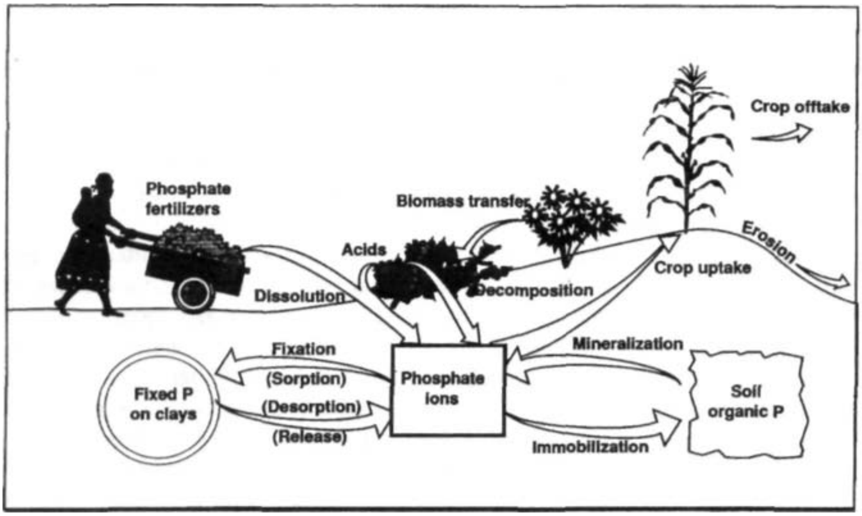

Fig. 1-2. Main features of the P cycle in smallholder farms of Africa.

from outside the field. The P content of plant residues and manures is normally insufficient to meet crop requirements. Plant materials applied as organic inputs contain 8 to 12 kg P ha^{-1} when applied at the top realistic rate of 4 t dry matter ha^{-1} (Palm, 1995). This is about one-half the P requirements of a 4 t ha^{-1} maize grain crop, which accumulates about 18 kg P ha^{-1} in its tissues (Sanchez, 1976). Phosphorus, unlike N, is not captured from the atmosphere by biological fixation nor from deep in the soil profile, due to the very low concentrations of available P in the subsoil and low root-length densities (International Atomic Energy Agency, 1975). Consequently, P fertilizers are almost always necessary to overcome P depletion (Breman, 1990; Mclntire & Powell, 1995).

The gathering of green plant material from boundaries or adjacent fields and their addition to another field is known as biomass transfer. Most of the biomass transfers practiced by African farmers consists of leguminous plants and grasses. There is increasing evidence, however, that some nonleguminous shrubs may accumulate higher than normal concentrations of P in their biomass than legumes. Tithonia *[Tithonia diversifolia* (Hemsley) A. Gray], a common farm hedge species native of Mexico and found at middle elevations throughout tropical Africa (Niang et al., 1996; Palm et al., 1997a) and southeast Asia (Nagarajah & Amarasiri, 1977; Nagarajah & Nizar, 1982; Cairns & Garrity, 1998) has unusually high concentrations of P (0.27-0.38% P or 2.7-3.8 g kg^{-1}) in its leaf biomass (Gachengo, 1996; Nziguheba et al., 1998). These levels are far superior to those in commonly used legumes in agroforestry and as herbaceous cover crops, which range in the order of 0.15 to 0.20% P (1.5-2.0 g kg^{-1}; Palm, 1995). Reasons for such high concentrations remain speculative but members of the Asteraceae (Compositae) family, to which tithonia belongs, are effective nutrient scavengers (Szott et al., 1991; Garrity & Mercado, 1994).

Internal Flows

Plants absorb phosphate ions, which come into the soil solution through the dissolution of P-bearing weatherable minerals, the dissolution of P fertilizers, the desorption of sorbed P, and the mineralization of soil organic P. Mycorrhizal associations facilitate the capture of phosphate ions by effectively enhancing the volume of soil exploited by roots and the efficiency with which P is extracted (Lajtha & Harrison, 1995). Mycorrhizae are key facilitators for P capture by plants in P-depleted soils (Tinker, 1975; Hedley et al., 1995).

Dissolution

The dissolution of P from the main P-bearing weatherable mineral in soils is only important in areas of Africa with soil derived from young alluvium or basic rocks high in P content. This is the case with many Vertisols and some calcareous and alluvial soils; however, weathering and rapid nutrient depletion have exhausted this source in most of the intensively cultivated lands of Africa. In soils derived from granitic or basaltic materials such as the bulk of Alfisols of the African subhumid and semiarid areas, the P reserves in weatherable minerals have always been low.

Sorption

Phosphate ions may be taken away from the soil solution and sorbed by Fe and Al oxides and hydroxides at the surface of clay particles. While these sorbed phosphate ions are unavailable to plants in the short run, they are slowly desorbed and released to the soil solution during a period of several years. Phosphorus sorption is considered the most important process controlling P availability in soils (Lajtha & Harrison, 1995) and has long been considered a major constraint to crop production (Sanchez & Uehara, 1980). Current systems thinking on sustainability, however, turns P sorption from a liability into an asset. Large applications of P fertilizers could become P capital as sorbed P. Subsequent P desorption is the service flow.

Phosphate sorption is controlled by clay surfaces and is only important in the topsoil where P fertilizers are applied. High P-sorbing soils, therefore, can be identified as those with clayey topsoils having red colors indicative of high contents of Fe and Al hydrous oxides, usually accompanied by a strong granular structure (Sanchez et al., 1982). These can be collectively termed oxidic soils,

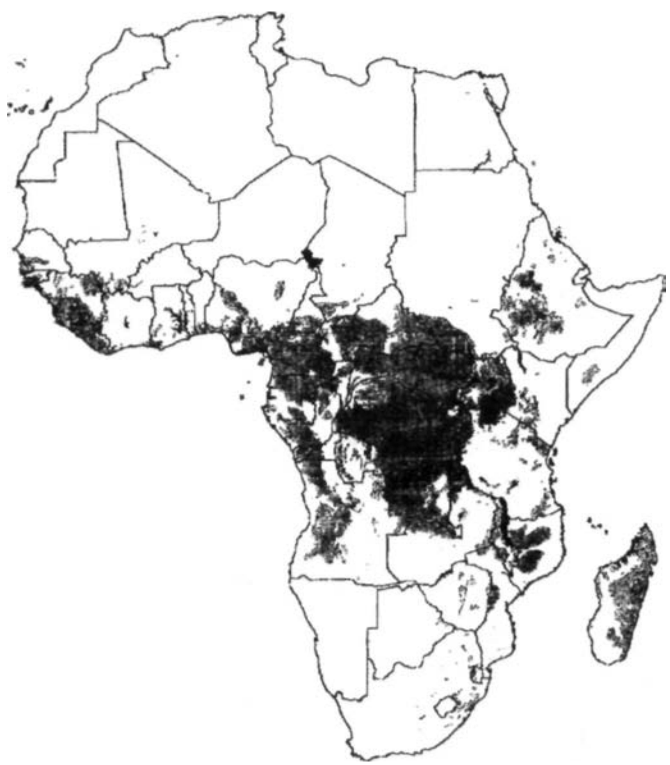

Fig. 1-3. ICRAF estimates a total of 530 million ha of P-fixing soils in Africa, shown in dark shading.

and are mainly classified as Oxisols, clayey Ultisols, rhodic, or oxic groups or subgroups of clayey Alfisols, and Inceptisols in soil taxonomy (Soil Survey Staff, 1992). In the FAO Legend they are classified as Nitisols, clayey Ferralsols, and clayey Acrisols (FAO, 1988). ICRAF estimates there are about 530 million ha of high P-sorbing soils in Africa, which represents 25% of tropical Africa's land area (Fig. 1-3).

It is important to recognize that we are excluding from consideration two other P-retention processes—those found in volcanic and in calcareous soils. P sorption in volcanic soils (Andisols) occurs in minerals collectively known as allophane. Upon P fixation these minerals actually open new P-sorbing sites, making them an ultimate sink for P with very slow desorption rates (Sanchez et al., 1982; Frossard et al., 1995). Therefore the capital stocks build up, but the service flows are minimal. Fortunately there are not many P-depleted volcanic soils in Africa, although these soils are locally important. Phosphorus also is retained in calcareous soils by precipitation with calcium carbonates, which results in the formation of calcium phosphates—apatites. The release of P from apatite is a straight solubility reaction, which is slow in high pH, high Ca soils. The magnitude of P fixation in calcareous soils is small, hence the growth in capital stock is small. The service flows are also small due to the low solubility of the product (Frossard et al., 1995). Consequently P-replenishment strategies are limited to soils with hydrous oxides of Fe and Al, which represent the bulk of smallholder farms in Africa.

Desorption

Most of the P sorbed by Fe and Al compounds is slowly released back to the soil solution, providing service flows for 5 to 10 yr. For example, 68% of a 150 kg P ha^{-1} application of diammonium phosphate (DAP) was recovered by a maize-bean rotation over 5 yr in an Oxisol of western Kenya (Heinemann, 1996). The residual effect of large phosphate applications is due to the desorption process, and in the Cerrado region of Brazil the duration of the residual effect increases with increasing rates of P application (Goedert, 1985).

Cycling

Plants convert inorganic P absorbed from the soil solution into organic forms in their tissues. The addition of plant material grown in situ to the soil as litterfall, root decay, green manure incorporation, crop-residue returns, and animal excreta (in grazing systems), and its subsequent decomposition results in the formation of organic forms of soil P. Microbes assimilate phosphate ions in the soil solution into organic forms in their biomass, a process referred to a P immobilization. Mineralization of soil organic P, including recently immobilized biomass P, releases it once again to soil solution P, which is readily available to plants, thus providing an additional service flow. This is the process of organic cycling.

Many trees, shrubs, and important crop species have the ability to exude organic acids from their roots or have mycorrhizal associations that help dissolve inorganic soil phosphates not otherwise available to crops (Lajtha & Harrison, 1995). Pigeonpea *[Cajanus cajan* (L.) Millsp.] secretes pisidic acid in calcareous soils (Ae et al., 1990) increasing the plant's P uptake. Inga *(Inga edulis* Mart.) is believed to have access to P not available to maize and beans (Hands et al., 1995). Pigeonpea and inga are legumes, which are known to acidify their rhizosphere in the process of N_2 fixation. In such cases, organic cycling has the advantage of transforming essentially unavailable forms of inorganic soil P into more available organic forms. Phosphorus depletion, however, can have serious negative effects on N cycling because adenosine triphosphate is needed in larger quantities for N_2 fixation by legumes than by plants that do not fix N (Giller & Wilson, 1991).

Outputs

The two main P loss pathways in Africa are crop-harvest removals and soil erosion (Smaling, 1993). Most of the P in cereal crops and grain legumes is accumulated in the grain and removed from the field at harvest. The proportion of P cycled back to the soil in grain crops, assuming complete crop residue return, is in the order of 40%, in contrast with about 50 to 70% for N and 90% for K (Sanchez, 1976; Sanchez & Benites, 1987). On smallholder farms in Africa, most crop residues are not returned to the field where they were produced because they are used for cattle fodder, fencing, or cooking fuel. This results in 100% removal of the P accumulated by crops for human nutrition.

While grain-harvest removal is a desirable outcome, soil erosion is environmentally dangerous since a P-enriched topsoil, if eroded, can cause eutrophication of surface waters (Sharpley et al., 1995). Losses of P by leaching are rare, except in very sandy soils, such as those in the Sahel (Brouwer & Powell, 1995).

Replenishing Phosphorus Capital

Replenishing P capital can only be accomplished with P fertilizer inputs. Experiences in the high P-sorbing soils of the Cerrado region of Brazil during the last 30 yr have shown that large applications of P can replenish P and the residual effect of such replenishment lasts for at 5 to 10 yr (Lopes, 1983, 1996; Goedert, 1985, 1987; Lopes & Guilherme, 1994). These corrective applications, along with subsequent maintenance applications, sound agronomic practices, and an enabling policy environment revolutionized farming in the Cerrado, which is now a major food-exporting region (Ableson & Rowe, 1987; Sanchez, 1994; Lopes 1996). Farmers who used P as a capital investment in the Brazilian Cerrado, along with annual applications of lime and other inputs, achieved internal rates of return on their investment of 96% (Ribeiro, 1979). This experience lends support to this concept for Africa.

Strategic options include a one-time application of P versus repeated smaller applications, and the use of PR vs. soluble P fertilizers. These options are directly related to two key soil properties: P sorption capacity and soil acidity. A one time corrective application in the order of 150 to 500 kg P ha^{-1} of TSP is probably the most straightforward way to replenish P capital and the effect lasts for several years in high P-sorbing soils (Yost et al., 1979; Goedert, 1987). High-reactive PR can be used in acid soils with similar agronomic efficiencies as superphosphates, but seldom in soils with pH values above 6.2 (Goedert & Lobato, 1980; Yost et al., 1982; Goedert, 1985; Frossard et al., 1995; Buresh et al., 1997, this publication). In sandy soils of the Sahel, where both P sorption and P availability are extremely low, medium-reactive PRs applied at low rates (15 to 30 kg P ha^{-1}) have relative agronomic efficiencies of 68 to 104% within a 3-yr period (Bationo & Mokwunye, 1991).

Phosphate Fertilizer Sources

Sub-Saharan Africa has vast quantities of PR deposits of varying quality, some of which are of sedimentary origin and reactive (McClellan & Notholt, 1986; Van Kauwenbergh et al., 1991; Buresh et al., 1997, this publication). High- to medium-reactive (>15 g citrate-soluble P kg^{-1}), sedimentary PR deposits are found in Angola, Burkina Faso, Mali, Niger, Senegal, and Togo, while highly reactive biogenic PR deposits occur in Tanzania and Madagascar. Most of these materials have been found to be suitable for direct application, while others are only effective when partially acidulated, applied in combination with soluble P fertilizers, or mixed with organic inputs (Hammond et al., 1986; Bationo et al., 1986, 1990; Bationo & Mokwunye, 1991; Buresh & Tian, 1997; Buresh et al., 1997, this publication). Igneous PR deposits, found in Burundi, Congo, Kenya, South Africa, Uganda, Zambia, and Zimbabwe are seldom suitable for direct application and are best used to manufacture superphosphates or modified as partially acidulated or compacted PR (Bationo & Mokwunye, 1991; Buresh et al., 1997, this publication).

The choice of P source also depends on many other factors, such as cost differentials between PR and superphosphate, soil acidity, and the P sorption capacity of the soil. Cost differences per kg P can be major, with locally produced highly reactive PRs having a competitive advantage in some instances. The more acid the soil, the more rapid the dissolution rate of PR. The soil and the superphosphate factory basically operate in the same way, dissolving PR with the addition of acids (Sanchez & Salinas, 1981). Furthermore, high P sorption enhances the dissolution of PR by reducing the concentration of P in solution around the PR particle (Smyth & Sanchez, 1982; Kirk & Nye, 1986).

Residual Effects

The duration of crop yield responses to P applications depends on the amount of P applied, the soil's P sorption, and cropping intensity. The larger the P application rate—the longer the residual effect. Low P-sorbing soils have shorter residual effects than high P-sorbing soils. The higher the number of crops harvested per year—the shorter the residual effect. Replenishment strategies for high P-sorbing, clayey, red soils of East and southern Africa will therefore differ from strategies for low P-sorbing, sandy soils of the Sahel, where smaller and more frequent applications are required (Bationo et al., 1996). Given these variables, as well as logistical, financial, and infrastructure considerations, the choice of P fertilizer source and the rate used for replenishment is site and situation specific.

Combining Inorganic and Organic Phosphorus Inputs

One of the problems of P replenishment in Africa is that acidifying agents are likely to be needed to facilitate the dissolution of PR. Many P-depleted African soils have pH values above 6.2, which as stated earlier, are too high for rapid dissolution of reactive PR. The decomposition of organic inputs produces (i) organic acids that may help acidify PR or (ii) chelating agents that bind Ca dissolved from PR and thus stimulate the further dissolution of the PR. Mixing PR with compost has been shown to increase the availability of African PRs in at least two cases: Kodjari PR in Burkina Faso (Lompo, 1993) and Minjingu PR in Tanzania (Ikerra et al., 1994). Another option might is to mix finely-ground PR with poultry or cattle manure prior to application to nonacid soils.

Organic anions produced during the decomposition of plant materials may temporarily reduce the P-fixation capacity of soils by binding to the Fe and Al oxides and hydroxides at surfaces of clay particles (Iyamuremye & Dick, 1996). Nziguheba et al. (1998) found that the rapid decomposition of 5.5 t ha~' of tithonia dry biomass reduced the P sorption and increased the available P pools of an acid soil during a 16-wk period. This was attributed to the blocking of P sorption sites by organic anions produced during biomass decomposition. Through such a process, P availability and nutrient-use efficiency are temporarily increased during a grain crops' growth period. In contrast, no such effect has been observed with senna *(Senna spectabilis* DC; Gachengo, 1996). Indeed, little is known about the influence of organic materials on P solubilization and sorption-desorption processes when organic materials are applied along with inorganic fertilizers (Palm et al., 1997b, this publication).

On-farm research in western Kenya illustrates the potential on combining inorganic and organic sources of P in a moderate P-sorbing Oxisol with pH 5.1. Minjingu PR and TSP were the inorganic P sources applied either with 1.8 t ha^{-1} of tithonia dry biomass or with an equivalent N rate as urea (60 kg N ha"[1]). Results of the first crop (Fig. *1-4)* show that the application of tithonia without P fertilizer doubled maize yields in comparison with the equivalent N rate as urea.

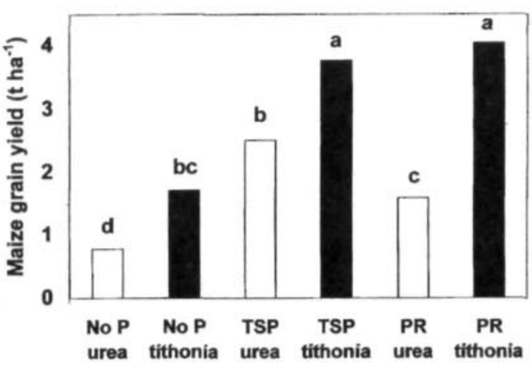

Fig. 1-4. Effect of combining tithonia biomass transfer (1.8 t dry biomass ha^{-1}) with Minjingu phosphate rock (PR) and triple superphosphate (TSP), both applied at 250 kg P ha^{-1}, on maize grain yield on an acid soil in western Kenya. Urea and tithonia were applied at 60 kg N ha^{-1} (adapted from ICRAF, 1997; Sanchez et al., 1997).

The combination of tithonia biomass transfer with the replenishment rate of 250 kg P ha^{-1} as Minjingu PR increased maize yields fivefold (from 0.8 to 4.01 ha^{-1}). Tithonia combined with 250 kg P ha^{-1} eliminated the differences in maize yield response between TSP and Minjingu PR (Sanchez et al., 1997; ICRAF, 1997). Maize crops in subsequent seasons are showing the same trends. The benefit from tithonia is partially attributed to addition of 60 kg K ha^{-1} with the plant material. Subsequent research confirmed higher maize production with the sole application of tithonia biomass than with an equivalent rate of N-P-K as inorganic fertilizer in a soil deficient in N, P, and K (Bashir Jama, 1997, personal communication).

Techniques to replenish soil P therefore, consist of P fertilization together with the effective use of organic sources. The integration of locally available organic resources with commercial P fertilizers may be the key to increasing and sustaining levels of P capital in smallholder African farms.

Economic Considerations

If P fertility is to be replenished for a number of years by a large, one-time capital investment, then the net present value (NPV) of the stream of net benefits generated by the P investment over a number of years should exceed zero at the chosen discount rate. In other words, the discounted value of the increased production, aggregated over the number of years the investment continues to provide benefits, must exceed the cost of the investment.

Even if P replenishment meets this criterion and is privately profitable for the farmer, the credit market imperfections previously discussed, and the extreme poverty of many farmers will mitigate against the adoption of P replenishment without some form of outside assistance. The P replenishment strategy should be promoted mainly in regions that are known to have large areas of P deficient soils that have P-sorption capacity. In such areas, the aggregate private returns to P replenishment are likely to be the greatest benefit, but externalities generated by P replenishment at a wide scale provide additional societal benefits (poverty alleviation, food security, employment effects, enhanced C sequestration, and biodiversity conservation). Under conditions of missing capital and information markets, assistance to farmers in replenishing P may be necessary in order for the potential private and social benefits of P replenishment to be realized.

REPLENISHING NITROGEN

Phosphorus replenishment must usually be accompanied by N replenishment in order to be effective, because most P-deficient soils also are deficient in N; however, replenishing N stocks to near their original levels would require very large inputs of organic N. For example, an increase in soil organic N concentration from 0.1 to 0.3% N (1-3 g N kg^{-1}) in the topsoil (0.2-m deep with a bulk density of 1.0 Mg m^{-3}) is equivalent to an application of about 160 t ha^{-1} of dry biomass (2.5% N or 25 g N kg^{-1}) or 8700 kg ha^{-1} of urea. Such large applications are clearly impractical and environmentally undesirable. In the short to medium term, increased soil N supply will depend on regular applications of N inputs.

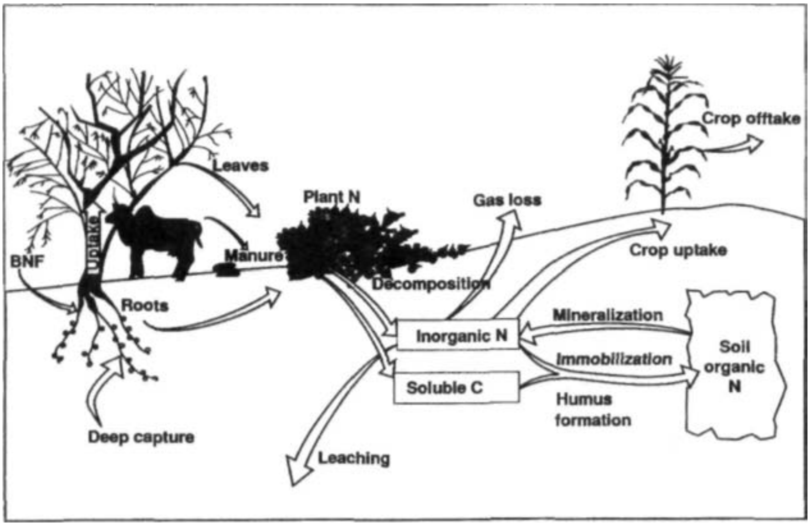

Fig. 1-5. Main features of the N cycle using organic inputs in smallholder farms of Africa.

The gradual rebuilding of N capital is a worthwhile objective, however, to provide buffering against uncertainty in the farmers' ability to supply N inputs to every crop. As indicated by Giller et al. (1997, this publication) the main issue in N replenishment is not the size of the capital N stocks, but the cycling rate. Therefore, appropriate strategies are those that will provide sufficient levels of N inputs while crops are growing, and at the same time slowly rebuild N stocks.

Nitrogen cycling consists of various inputs, outputs, and internal flows at the field scale (Fig. 1-5). Nitrogen capital stocks include the labile pools of soil organic N, such as microbial biomass N and N in the light fraction of SOM, which are correlated with N mineralization rates (Barrios et al., 1996; Kapkiyai, 1996). Given the largely biological nature of the N cycle, organic inputs play a crucial role in N replenishment.

Inputs

Nitrogen inputs to a field consist mainly of inorganic fertilizers, biomass transfers, BNF, animal manures or composts produced outside the field, and nitrate capture from subsoil depths beyond the reach of crop roots. BNF becomes an input upon the conversion of atmospheric N_2 gas into plant N by symbiotic plants followed by the addition of plant N to the soil.

Inorganic fertilizers account for about one-third of the N inputs in Africa (Smaling, 1993), but they are used largely in mechanized agriculture and on export crops. Only three countries in sub-Saharan Africa—Nigeria, Zimbabwe, and South Africa—produce N fertilizers. Millions of smallholder farmers throughout Africa, however, use N fertilizers, most of which are imported. Heisey and Mwangi (1996) reported that 37% of the area planted to maize in 11 African countries received N fertilizers in the early 1990s. Because of the high price imported fertilizers at the farm gate and delays in delivery due to poor infrastructure (Donovan, 1996), smallholders often apply N fertilizer at too low rates and too late for obtaining good crop-yield responses (Heisey & Mwangi, 1996).

Most smallholder farmers apply cattle manure—usually collected from enclosures *(bomas, kraals)* where cattle spend the night—but at rates too low to meet crop requirements and prevent decreases in SOM content. In the Heisey and Mwangi (1996) study, manures accounted for <10% of N inputs in Africa, or about 1 kg N ha^{-1} yr^{-1}. In intensively managed smallholder areas like the Kisii District of Kenya, applications of manure to the fields from cattle enclosures average 23 kg N ha^{-1} yr^{-1}, or about one-half of the total N inputs (Smaling, 1993). Manure is often diluted with soil when shoveled from cattle enclosures, and its quality and nutrient composition also is affected by the quality and quantity of fodder the animals eat (Murwira et al., 1995; Probert et al., 1995). The value of manure as a source of N ranges from high-quality manure that increases crop yields to low-quality manure that depresses crop yields due to N immobilization, with a critical threshold value of 1.25% N (12.5 g N kg^{-1}; Mugwira & Mukurumbira, 1986).

The management of BNF is well established and practiced through the cultivation of N-fixing plants and the use of rhizobium inoculants (Giller & Wilson, 1991; Giller et al., 1997, this publication). Trees provide N inputs in agroforestry systems by two processes, BNF and deep-nitrate capture. Grain legumes and herbaceous green manures supply N principally through BNF. Although the magnitude of BNF is methodologically difficult to quantify, overall estimates are in the order of 25 to 100 kg N ha^{-1} per crop for grain legumes and as much as 280 kg N ha^{-1} yr^{-1} for some herbaceous and woody perennials (Giller & Wilson, 1991). BNF can supply considerable N inputs to crops via litter decomposition in soils, as long as these soils have enough available P.

Legume cereal intercrops are widely grown as a means of reducing the risk of crop failure and providing households with improved diets. The potential N replenishment of a grain legume is a balance between fixed N and N in harvested products (Giller & Cadisch, 1995). Unfortunately the potential for net N inputs by BNF with grain legumes is quite limited. Nitrogen fixation by peanut *(Arachis hypogea* L.) ranges from 68 to 206 kg N ha^{-1} per crop, but most of it is removed at harvest (Giller & Wilson, 1991). Common bean is widely cultivated in East Africa, but it has such a low inherent capacity to fix N that it is likely to produce a negative N balance in the soil (Giller & Cadisch, 1995). Soybean *[Glycine max* (L.) Mem] has a high BNF capacity, but it concentrates N in the pods, adding little to the soil. Therefore, the contribution of BNF by commonly grown grain legumes with high N harvest index does not seem relevant to N replenishment.

Short-term fallows of leguminous trees and herbaceous cover crops, however, provide a practical means of N replenishment via BNF when grown in rotation with cereal crops. Two-year tree fallows of sesbania *[Sesbania sesban* (L.) Mem] or tephrosia *(Tephrosia vogelii* Hook, f.) have replenished soil N levels enough to grow three subsequent high-yielding maize crops in N-depleted, but P-sufficient soils in southern Africa (Kwesiga & Coe, 1994; Kwesiga et al., 1998). In Coastal West Africa, 6-mo herbaceous fallows of mucuna *[Mucuna pruriens* var. *utilis* (L.) DC] supply the N needs of one subsequent maize crop (Osei-

Bonsu & Buckles, 1993; International Institute of Tropical Agriculture, 1995; Manyong et al., 1997; Galiba et al., 1997). In general, woody fallows accumulate larger N stocks than herbaceous ones because of their larger and continuing biomass accumulation (Szott et al., 1998). The residual effects of tree fallows are therefore longer than those of herbaceous fallows.

There is evidence that non-N-fixing trees and shrubs of the genus *Senna* and *Tithonia* accumulate as much N in their leaves as N-fixing legumes, presumably because of their greater root volume and ability to scavenge nutrients from the soil (Szott et al., 1991; Garrity & Mercado, 1994, Gachengo, 1996). But it is important to note that these nonfixing trees are only *cycling* the N present in the soil, not adding *inputs* to the system, as happens via BNF in woody and herbaceous leguminous fallows. Non-N-fixing trees and shrubs can only be considered to be N inputs when biomass is transferred from one field to another.

Tree roots are often able to capture nutrients at depths beyond the reach of most crop roots. This can be considered an additional nutrient input in agroforestry systems when such nutrients are transferred to the topsoil via the incorporation and subsequent decomposition of tree litter. Hartemink et al. (1996) and Buresh and Tian (1997) detected subsoil nitrate levels in the order of 70 to 315 kg N ha^{-1} at 0.5- to 2-m depth in maize-based systems on Oxisols and Alfisols of western Kenya. They also found that sesbania fallows depleted this pool, thus capturing a resource that was unavailable to maize crops (Mekonnen et al., 1997; Fig. 1-6). The source of this nitrate pool is believed to be the result of the mineralization of organic N in the topsoil, which is relatively high in these soils, followed by nitrate leaching into subsoil layers. The nitrate anions are then held in the oxidic subsoil by positively charged clay surfaces.

Subsoil nitrate accumulation and its depletion was detected in East Africa decades ago (Mills, 1953; Kabaara, 1964), but such findings were not given practical attention at that time. It is probable that trees also capture K at same depths in similar soils and thus help prevent K deficiencies. In order for nitrate anions *to* move, they must be accompanied by a cation; K is the main leachable cation in such soils.

Nitrate accumulation in the subsoil is well documented in soils with subsoils rich in Fe oxides that provide anion-exchange sites to hold nitrate ions (Kinjo & Pratt, 1971; Black & Waring, 1976; Cahn et al., 1992). Many such subsoils, however, are highly Al-toxic, preventing significant plant root development, but subsoil acidity is not a widespread constraint in African soils cultivated by smallholder farmers.

The rotation of annual crops with short-duration fallows containing deep-rooted perennials holds promise as a way to use subsoil nitrate that would otherwise be unavailable to crops. This resource may not be replenished when cropping systems become more intense, as nitrate leaching from the topsoil may be diminished by more extensive crop root systems. The magnitude of captured subsoil nitrate needs to be assessed in other soils, but soil chemistry indicates that subsoil nitrate accumulation will not be as significant in many other types of soils found in Africa. Nevertheless, there are 260 million ha of oxidic soils in Africa that have anion-exchange capacity in the subsoil. The use of this hitherto unrec-

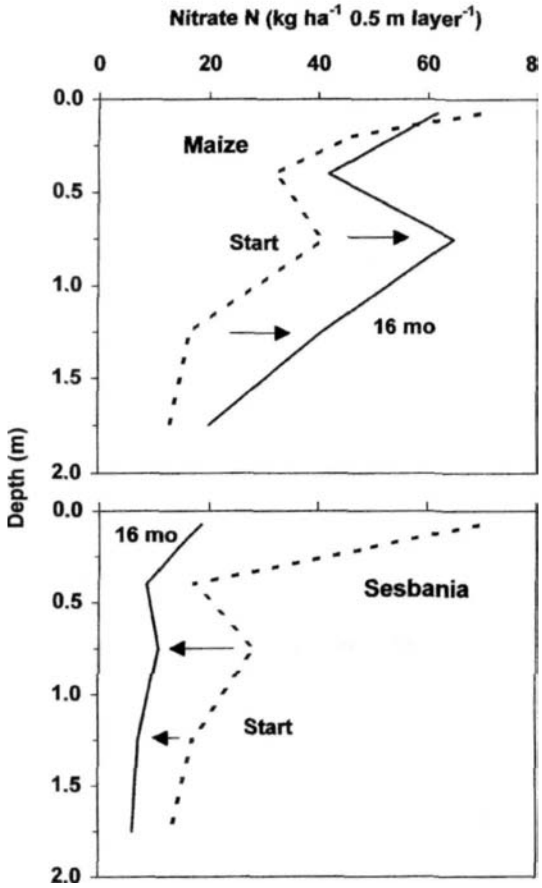

Fig. 1-6. Evidence of a subsoil nitrate accumulation and its capture by a sesbania tree fallow on an Oxisol of western Kenya.

ognized N source via its capture by deep-rooted trees is an exciting area of research in regions with oxidic, but not Al-toxic subsoils.

Internal Flows

Considering the inconsistent use of N fertilizers and the very limited returns of crop residues to the soil, most of the internal N cycling in maize-based smallholder systems in Africa results from the mineralization of soil organic N (Woomer et al., 1997). Such process may contribute most of the N required for low-yielding grain crops, until the labile soil organic N fractions (N capital) are depleted. Incorporating N-fixing trees and herbaceous legumes into the farming system enhances nutrient cycling and also provides the organic C and N necessary for maintaining N capital (Palm, 1995).

Outputs

A typical maize crop in smallholder African farms yields <1t ha^{-1} of grain and requires a plant accumulation of <40 kg N ha^{-1}; a 41 ha^{-1} maize crop requires 100 kg N ha^{-1}, and a 7 t ha^{-1} maize crop requires 200 kg N ha^{-1} (Sanchez, 1976). Approximately two-thirds of this N is accumulated in the grain and will be exported during harvest. Much of the remaining N is located in the stover and will not necessarily be cycled back to the soil because crop residues are frequently burnt, sold, or fed to livestock, and the manure produced is applied to higher-value crops growing in other fields. Loss processes such as soil erosion, leaching, and denitrification represent N outputs. In sandy soils of the Sahel, 26 to 47% of the surface-applied urea is lost through ammonia volatilization (Christianson & Vlek, 1991).

Can Nitrogen Demands be Met Biologically?

Herbaceous leguminous cover crops provide sufficient N inputs through BNF to meet the needs of one subsequent maize crop. In Africa, the main species used are of the genus *Mucuna, Crotolaria, Pueraria, Dolichos,* and *Desmodium* (Balasubramanian & Blaise, 1993; Wortmann et al., 1994). The use of mucuna in short-term fallows interplanted with maize or planted during the dry season is expanding rapidly in Benin and Ghana (Osei-Bonsu & Buckles, 1993; Manyong et al., 1997). Mucuna fixes N and smothers imperata *[Imperata cylindrica* (L.) Rausch.] (International Institute of Tropical Agriculture, 1995). Herbaceous leguminous fallows because of their shorter duration and lower biomass accumulation provide lower N inputs than woody leguminous fallows (Szott et al., 1998).

Improved herbaceous and woody leguminous fallows, therefore, provide excellent options for managing N biologically, provided that the soil is sufficient in P and that farmers are willing to make land available for crop-fallow rotations. Empirical evidence in Benin, Ghana, and Zambia show that thousands of farmers are taking advantage of such an option (Galiba et al., 1997; Kwesiga et al., 1998).

At high-crop-yield levels comparable to those of commercial farms in the temperate zone (above 6 t ha"^{1} of maize grain), organic N inputs are likely to be insufficient and therefore must be supplemented with inorganic fertilizers. The senior author has seen some farmers in Chipata, Zambia doing this. They rely on 2-yr sesbania or tephrosia fallows to provide the basal N and then use N fertilizers at top dressing time if the rainfall is favorable and the crop shows N deficiency. If the expected production is not promising, farmers may save the N fertilizer for the next year. This is an excellent example of the strategic use of fertilizers (Sanchez, 1994).

Replenishing Nitrogen Capital

Organic inputs have an important advantage over inorganic fertilizers with regard to fertility replenishment—they provide a source of C for microbial use

(Fig. 1-5). According to Palm (1995), the recovery by the crop of N from the leaves of leguminous plants incorporated into the soil (10-30%) is generally lower than the recovery from N fertilizers (20-50%). Much of the remaining 70 to 90% of the applied organic N not used by crops or leached is incorporated into labile pools of soil organic N and C. Soil microorganisms require C substrate for growth and to use the N from organic inputs to form soil N capital. Part of the N bound in the more recalcitrant fractions in the organic inputs also will increase soil organic N (Giller et al., 1997, this publication). Inorganic fertilizers do not contain such C sources, and therefore much of the fertilizer N not used by crops is subject to leaching and denitrification losses in the absence of crop residue returns.

Long-term experiments in Africa provide indirect evidence in support of the combined organic and inorganic approach to replenishing N and C capital. Kapkiyai (1996) reports a 29% loss of total soil N (1.06t N ha^{-1} in the top 15 cm) when maize and beans were grown in rotation for 18 yr without nutrient inputs and with crop residues removed in Kabete, Kenya. The same loss took place in plots with the recommended fertilizer applications but no residues returned; however, when fertilizers and manures were added and the maize stover was retained, the decline in total topsoil N was reduced by one-half. Organic inputs or the recycling of crop residues apparently provided the soluble C necessary to reduce N depletion in this fertile soil.

In sandy soils of the Sahel, Pieri (1989) also found that additions of N fertilizer alone did not increase soil C or N stocks. But fertilizers plus organic inputs (crop-residue returns, manures, and composts) increased soil N and C stocks, except in extremely sandy soils where there are too few clay particles to protect newly formed SOM from decomposition.

There are some extreme situations in Africa where virtually all organic resources are depleted or are used to meet more pressing needs. Much of the Central Ethiopian highlands have been converted from forest to smallholder agricultural landscapes essentially devoid of trees. Crop residues are fed to livestock, while manure and even roots are used as cooking fuel. Insecure land tenure discourages the replanting of trees, thus exacerbating the problem. To break clear of this vicious cycle, N fertilizers must be applied along with whatever organic inputs become available from planting trees.

Research to date has mainly compared inorganic vs. organic sources of N with little consideration of the nutrient content of organic sources. The quantitative interaction between organic and inorganic sources of N is essentially a new subject of research in the tropics (Palm et al., 1997b, this publication).

The joint organic-inorganic N replenishment strategy just described is not new; it has been used for centuries in temperate agricultural systems, where N fertilizers together with crop rotations, winter cover crops, manure applications, and the full incorporation of crop residues provide sufficient N and C inputs to gradually increase soil N and C stocks (Buol & Stokes, 1997, this publication). What is new is the potential to do something similar to replenish soil N in the tropics with systems that add N inputs in situ and are consistent with the constraints of smallholder farmers.

ACCOMPANYING TECHNOLOGIES

Soil-fertility replenishment requires a set of accompanying technologies and policies to be effective in raising and sustaining food production. By itself, soil-fertility replenishment is a necessary but not sufficient condition for increasing per capita food production in Africa.

Soil Conservation

First and foremost, soil erosion control technologies must be present in order to keep the nutrient capital investment in place and to prevent nutrient pollution of rivers, lakes, and groundwater. Where the labor to land ratio is high, such as in parts of the East African highlands, various labor-intensive soil conservation technologies are financially attractive and widely used (Cleaver & Schreiber, 1994). A P investment program that does not include contour hedges or other erosion control technologies is likely to do more harm than good. Fortunately, there are well-proven biological methods of erosion control, such as growing leguminous hedges or vegetative filter strips along the contours (Kiepe & Rao, 1994; Garrity, 1996). Soil conservation technologies are more readily adopted if they provide useful by-products. The technologies mentioned also can provide fodder, fuelwood, fruit, and biomass for transfer to adjacent fields. Farmers' willingness to undertake soil conservation measures will increase with population density and with policy reforms that make intensive farming more profitable (Cleaver & Schreiber, 1994).

Sound Agronomic Practices

There are several positive feedbacks to soil-fertility replenishment. It is more likely that sound agronomic practices will be profitable in replenished areas than in depleted ones. Such practices include the use of improved crop germplasm, integrated pest management, crop-residue returns, crop rotations, supplemental irrigation, and maintenance fertilization. Many of these practices are not worthwhile in nutrient-depleted soils because low crop yields give negative returns to such investments.

Fertility replenishment also enables farmers to intensify and diversify their production. They may shift from growing low-value crops to growing vegetables, livestock, or trees that produce high-value products, which may add economic sustainability through product and income diversification (Cleaver & Schreiber, 1994; Tomich et al., 1995; Sanchez & Leakey, 1997). Such diversification also will contribute to environmental resilience through increased plant biodiversity.

Some pest problems related to low soil fertility are diminished when fertility is replenished. For example, in addition to replenishing N, 1-yr fallows of *sesbania* have been found to encourage suicidal germination of the parasitic weed striga *[Striga hermonthica* (Del.) Benth.], a major maize pest in western Kenya, reducing its seed pool by one-half (Oswald et al., 1996; Amadou Niang, 1997, personal communication).

Some negative feedbacks also are likely to occur. New pest problems may arise as a result of increased soil fertility because of higher plant biomass and moisture in the fields. Deficiencies of other nutrients, such as K, may become evident due to the higher nutrient offtake by high-yielding crops. In such cases, however, the added fertilizer requirement should not be considered a capital investment but a recurring cost of production that should be paid for by increasing crop yields.

MAKING REPLENISHMENT OPERATIONAL

Specific districts or other divisions of a country that are affected by severe nutrient depletion can be identified for nutrient replenishment projects. Project development is best designed and conducted with farmers and communities to assure their involvement from the beginning (Ashby, 1986, 1987).

Case studies are useful in bringing a more direct perspective. We describe three recent case studies in biophysically and socioeconomically contrasting areas of Africa: (i) western Kenya, a densely populated, high-potential area with N and P depletion, high P-sorbing soils, and secure land and tree tenure, (ii) eastern Zambia, a less densely populated, medium potential area with soils depleted only of N and secure customary land and tree tenure, and (iii) Central Burkina Faso, the least densely populated area with low potential, low initial levels of N and P, insecure land tenure, and no tree tenure.

Western Kenya Case Study

Characterization

The highlands of western Kenya, which are part of the Lake Victoria Basin, have one of the densest rural populations in the world—500 to 1200 people km"^{2} (Hoekstra & Corbett, 1995). Annual rainfall ranges from 1200 to 1800 mm with a bimodal distribution. Elevation averages 1200 m, and the main soils are high P-sorbing Alfisols and Oxisols, originally quite fertile but now widely depleted of N and P. Characterization studies identified declining soil fertility as the main factor limiting crop production (Hoekstra, 1988).

There are about 6 million people and 2 million farms in a total area of 10 000 km^2, with an average farm size of 0.5 ha of which about one-third is planted to maize. With maize yields often as low as 1 t ha^{-1} over two seasons and households needing >1000 kg yr^{-1} of maize for food security, most households are only producing enough maize to feed themselves for a few months. They must purchase maize on the market during the remaining months or endure hunger periods.

About 80% of farms in Vihiga, Siaya, Busia, and Kisumu Districts are severely deficient in P (<5 mg bicarbonate-extractable P kg^{-1} soil), and most are deficient in N when P deficiency is overcome (Shepherd & Soule, 1998; Bashir Jama, 1997, personal communication). Heavy striga infestations frequently occur in N-depleted soils. The irony is that the main soils of the region (Rhodudalfs and

Table 1 - 1 . Basket of choices to replenish soil fertility in small farms of western Kenya.

Interplant an improved fallow of Sesbania, tephrosia, or crotolaria *(Crotolaria grahamiana* Wight & Am.) during the long rains into the maize crop and after the second weeding. Let the fallow grow for about 1 yr. The fallows will decrease the seed pools striga by about 50% and add about 150 kg N ha^{-1} to the soil.

Construct contour bunds, ditches, or terraces and plant tithonia along them after the maize harvest to ensure erosion control in future replenished fields.

Plant additional tithonia in hedges along farm and field boundaries or in vacant land to accumulate about 0.7 t of fresh biomass every 6 mo per farm (about 500 m of 1-m-wide hedges). Transfer tithonia biomass to the fields (at the rate of 2 t dry material ha^{-1}) before maize planting. Tithonia adds about 60 kg N, 6 kg P, and 60 kg K ha"[1] to the soil and increases the availability of P fertilizers.

Apply other organic resources such as compost and cattle manure produced on farm.

Apply a reactive phosphate rock (PR) at the average replenishment rate of 250 kg P ha"' to 0.3 ha per farm, and incorporate it with tithonia and the leaf materials from leguminous fallows. The residual effect of P is expected to last for 10 subsequent crops.

Shift some of the replenished fields from maize to high-value vegetables such as sukuma wiki *(Brassica oleracea* var. *acephala)* or eventually agroforestry trees that also produce high-value fruits, pharmaceuticals, or high-grade timber.

Eutrudoxs) are considered among the most productive soils of the tropics (Sanchez, 1976).

Farmers realize the value of fertilizers in western Kenya. About 40% of them use some DAP, but at lower than recommended rates and often too late for optimum timing of applications (Swinkels et al., 1997). In spite of the extreme land pressure, about 52% of the fanners leave a portion of their farm in weedy fallows (Swinkels et al., 1997). Fallowing is often not a matter of choice, because either the land is severely depleted or labor and agricultural inputs are not available (Amadou Niang, 1997, personal communication). This provides an entry point for the organic inputs to be grown in situ.

Action

Five years of collaborative research have shown that the use of organic and inorganic inputs can replenish soil fertility and decrease striga infestations to manageable levels. In addition to researcher-managed on-farm trials, there are currently a total of about 1000 farmers experimenting with the improved technologies through district extension services, NGOs, and a team of national and international centers working there as part of the African Highlands Initiative (Wang'ati & Kebaara, 1993; ICRAF, 1996). About one-half of the farmers are experimenting with improved fallow technologies, the rest with biomass transfer technologies, and a few with P fertilizers. Okalebo and Woomer (1996) suggest the target should be to replace P lost over 20 yr (an average of =250 kg P ha^{-1}) in farmers' fields where P is the most limiting nutrient. Here, the use of PR appears promising due to its sub-regional availability, suitable soil pH, and price advantage. The replenishment strategy is based on the steps shown in Table 1-1. Some research results have been shown in Fig. 1-4.

Impact Models

The first step in analyzing the feasibility of a replenishment strategy is determining if it is profitable at the farm level. An economic-ecological farm model for assessing the impact of soil-fertility replenishment on farm income and nutrient balances has been developed for the East African highlands (Shepherd & Soule, 1998). This or similar models can indicate the potential profitability and adoptability of new practices as well as their ecological consequences.

The model simulates the impact of current and improved agroforestry and other soil-management practices at the farm scale on nutrient availability, nutrient cycling and losses, and plant and livestock production. It also provides various measures of financial returns. Farm size, crop allocation, and soil-management practices are based on typical values for farmers with different levels of resource endowment.

Simulations have been carried out to analyze the farm-level impact of P and N replenishment for farmers with low- and high-resource endowments in the densely populated Vihiga District of western Kenya. Soils in the district are generally high P-fixing and P-deficient. A typical low-resource farmer has about 0.2 ha of land and grows mainly maize and beans. About 55% of the farmers in the district have been classified in the low-resource endowment category, and 35% of the farmers are classified in the medium-resource endowment category. Both categories have per capita incomes of <1 U.S. dollar per day (ICRAF 1996; Narayan & Nyamwaya, 1995). High-resource endowment farmers make up only about 10% of the farming population. They typically have about 1.6 ha and farm more intensively, incorporating dairy cows *(Bos taunts)* and significant amounts of purchased inputs (Shepherd & Soule, 1998).

Simulations over 20 yr were made of the existing system and three improved systems based on a one-time investment dressing of Minjingu PR (250 kg P ha^{-1}) with three alternative sources of N: (i) urea at the rate of 60 kg N ha^{-1} yr^{-1}, (ii) transfer of green biomass of tithonia from existing farm borders (1.9 t dry green biomass ha^{-1} yr^{-1}, producing 60 kg N ha^{-1}), and (iii) improved fallow of sesbania grown on one-half of the field area and rotated with the maize and bean crops.

For the low-resource endowment farmers, the simulation results demonstrate large potential increases in crop yields from P replenishment (Fig. l-7a), whichever source of N is used. Nitrate leaching (Fig. 1—7b) is initially highest in the existing system (no inputs) because the N mineralized from organic matter cannot be fully used by the P-limited crops, but N leaching in this system declines as SOM levels decline. When P is applied nitrate leaching is reduced, especially in the tree-based improved fallow system (IF). Soil organic P (Fig. l-7c) decreases under the existing system, but it is maintained or increased with P replenishment.

Profitability

Net farm income (the value of crop output less the cash costs of production) increased by 80 to 160% over the existing system by Year 2 of the simulation (Fig. l-7d); however, farm returns, which is net farm income less family labor valued at the market wage, is lower with biomass transfer (BT) than with urea or IF due to the large labor requirement of BT. Farm returns will vary with the actual opportunity cost of labor, which is probably below the market wage (U.S. dol-

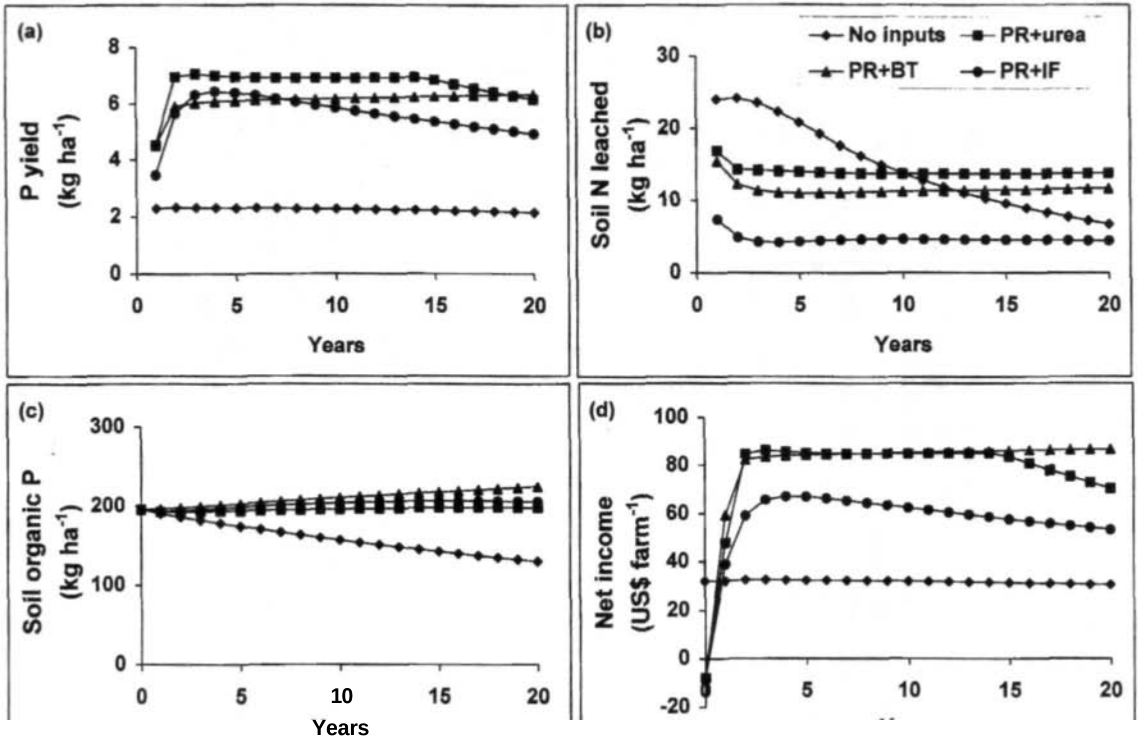

Fig. 1-7. Simulations for four alternative land use systems for a typical resource-poor farm (0.2 ha) in western Kenya. No nutrient inputs, phosphate rock (PR) at 250 kg P ha^{-1} plus urea at 60 kg N ha-[1], PR plus biomass transfer (BT) from farm boundaries, and PR plus improved fallow (IF) with sesbania. P yield is P in harvested products (maize and bean grain and fuel wood). Soil N leached is at 2-m soil depth. Net income is based on 1 US$ = 55 Kenya shillings.

Table 1-2. Simulated net present values (NPV) based on a discount rate of 20% and investments for four alternative land-use systems for a typical resource-poor farm (0.2 ha) in western Kenya. The four land-use systems are the existing system, which is based on maize-bean intercropping and use no external nutrient inputs, and three improved systems each with an investment dressing of 250 kg P ha^{-1} as phosphate rock (PR) and then either urea at 60 kg N ha^{-1} yr^{-1}, transfer of biomass of tithonia (1.9 t dry biomass ha^{-1}) from farm boundaries, or an improved fallow of sesbania on one-half of the field area each year. 1 US$ = 55 Kenya shillings.

Parameter	Existing system	PR + urea	PR + biomass transfer	PR + improved fallow
	US$			
NPV of net farm income	157	342	350	250
NPV of farm returns	17	201	107	169
Investment in P (first year only)	0	40	40	40
Annual N investment	0	8	0	5

lars 0.90 d^{-1}) for the low- and medium-resource farmers but close to the market wage for the high-resource category.

At a discount rate of 20%, the NPV of net farm income and farm returns are much higher for all three replenishment scenarios than for the existing system (Table 1-2), suggesting that P replenishment is indeed profitable for low-resource farmers with P-deficient and high P-sorbing soils. Whether an individual farmer might prefer to combine PR with urea, improved fallow, or biomass transfer depends on the cash and labor constraints faced by that farmer; however, the initial investment required for P replenishment (U.S. dollars 40 per 0.3 ha per farm) is greater than the annual farm income generated by the existing system and about 10% of the average annual household income of about U.S. dollar 420 for a low-resource farmer (Shepherd & Soule, 1998). Such households are unlikely to be able to undertake an investment in PR without some form of financial assistance.

The high-resource endowment farmers, on the other hand, do not profit from P replenishment since their current practices already include annual P inputs and large manure applications from their dairy enterprise. Years of good land husbandry have maintained soils at productive levels. The high-resource endowment farmers are able to farm profitably and sustainably because they are not as severely affected by capital, labor, and information constraints as are small, low-resource farmers. For high-resource farmers, the capital constraint has been released by access to significant amounts of off-farm income. Indeed, high-resource endowment farmers are partly defined by their access to off-farm income and the use of such income for on-farm investments (Crowley et al., 1996).

Eastern Zambia Case Study

Characterization

In less densely populated areas (20 to 40 people km^{-2}) of the eastern province of Zambia, an area typical of the Miombo woodlands of southern Africa (White, 1983), grass fallows of 1 to 5 yr coexist with maize cultivation, which in a sense is a form of shifting cultivation in tropical savannas. A diagnostic and design survey in Katete and Chipata Districts (Ngugi et al., 1988) revealed a serious breakdown of traditional strategies to sustain production of food, fodder, and fuelwood. Declining N fertility was identified as the major problem responsible for low yields of the main staple food crop, maize. Phosphorus is not yet an important constraint in this region. Maize no longer receives N fertilizers since the removal of subsidies, which tripled or quadrupled the cost of fertilizer N relative to the prize of maize (Heisey & Mwangi, 1996). There is a hunger period when the maize supplies run out before the next harvest. Given the relatively large farm size (3 to 5 ha) and the widespread use of grass fallows, improved fallows seemed the logical entry point in this area.

Action

The strategy developed was to use leguminous fallows to accumulate N from BNF, smother weeds, and improve soil physical properties (Kwesiga & Chisumpa, 1992). The main species identified were sesbania, tephrosia, and pigeonpea. Two-year-old sesbania or tephrosia fallows doubled maize yields during a 6-yr period, in comparison with continuous unfertilized maize production (Kwesiga & Coe, 1994; Kwesiga et al., 1998). This was accomplished in spite of 2 yr without crop production while the fallows were growing.

Research also is in progress on alternative sesbania cultivars and on other species, cheaper establishment methods such as bare-root seedlings, and combining improved fallows with top dressings of N fertilizers to push yields to a higher plateau (Kwesiga et al., 1998). Researchers also are examining farmer perceptions, local policies to protect the fallows from grazing, and the overall adoption potential (Franzel, 1998).

On-farm research started by establishing solid relationships with the extension staff, and through them to the farmers. The approach was initially to select a village near a farmer training center, which would later be used for demonstrations. Meetings were then arranged where both the researchers and extension staff

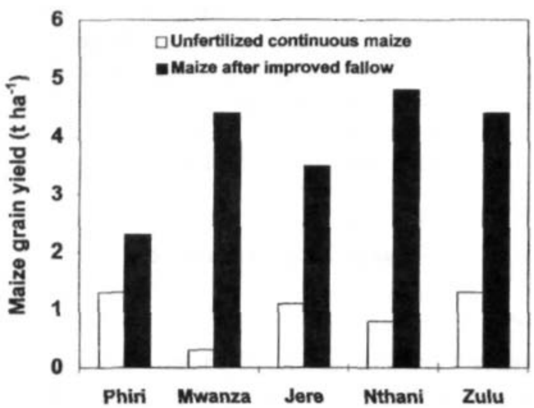

Fig. 1–8. Improved 2-yr fallows with sesbania increased maize yields in five farmer-designed and farmer-managed trials in eastern Zambia (Kwesiga et al., 1998).

interacted with farmers and discussed the causes of low maize yields, the farmers' fallowing practices, and the potential of improved fallows. Such visits generated much discussion among farmers and confirmed that the farmers were genuinely interested in the technology. The research-extension team increased the frequency of field days so that they coincided with the major phases of improved fallows: the nursery, the fallow, and crop (Kwesiga et al., 1998).

About 158 farmers initiated researcher-designed, farmer-managed trials, each with 400 m^2 plots of improved fallows. These farmers represented a range of high and low income, male and female, and oxen and hoe users. In the trials, farmers selected one of six options of improved fallow technologies. More than 70% planned to continue using the technology during the next season.

In farmer-designed and -managed trials, fanners were provided seed or seedlings and advice on options available, such as fallow length, tree density, and planting method. They were left to design their own trials, planting trees where they wished in their own farms. The main purpose of this type of trial is to understand how improved fallows are accepted by farmers into their existing farm practices. The number of farmer-designed trials increased from five in 1993, to 37 in 1994, and to 797 in 1995. Many farmers who initially started off as researcher-designed, farmer-managed trials also planted farmer-designed trials after experiencing the benefits of improved fallows. Usually, they produced planting materials in their own farms.

During 1996, five farmers harvested maize following 2- or 3-yr sesbania fallows. Maize yields were impressive (Fig. 1-8), and yields for four of the five farmers were comparable to those achieved from fully fertilized controls. These results, showing that sesbania fallows increased maize yields without fertilizers, triggered enthusiastic responses from a large number of farmers, extension staff, NGOs, and development agencies. The challenge now is to increase the technology adoption from 4000 farmers now practicing it (Kwesiga et al., 1998) to millions of farmers in southern Africa.

Profitability

The rotation of a 2-yr sesbania fallow followed by 3 yr of maize produced 92% more wealth (NPV of US$ 588 ha^{-1}) than the current situation, 5 yr of continuous maize cultivation without N inputs (Table 1-3). The most profitable option, however, was the recommended rate of N fertilizer (112 kg N ha^{-1} per crop)—an option most farmers are no longer able to consider.

Table 1-3. Cumulative discounted net benefits for 2-yr sesbania improved fallows followed by 4 yr nonfertilized maize as compared with continuous maize cropping at Chipata, Zambia, with a discount rate of 20% (Kwesiga et al., 1998).

Land-use systems	Cumulative discounted net benefit					
	1988	1989	1990	1991	1992	1993
	US$ ha^{-1}					
Continuous maize, no fertilizer	119	201	235	310	299	307
2-yr sesbania fallow-nonfertilized maize	-171	-151	175	475	488	588
Continuous maize (112 kg N ha^{-1} yr^{-1})	483	844	1054	1195	1153	1303

The returns to labor may be more important to farmers than the returns to land in this area, where labor is more scarce than land. The returns to labor from a 2-yr fallow, 3-yr maize rotation were US$ 3.45 per day, which is 70% more than from continuous monocropped maize without fertilization. If farmers plant 2 ha of maize after 2-yr fallows every year, they would overcome food insecurity and achieve a maize surplus of 205%, except in drought years.

Numerous sensitivity analyses were undertaken (ICRAF, 1995). They included changes in the wage rate, cost of seedlings, maize yields, and fuelwood prices and an investigation into how changing occurrences of drought affected fallow performance. In virtually all reasonable scenarios, the 2-yr fallow was shown to be more attractive than the existing practice except for one with an extremely high discount rate (over 40%).

Central Burkina Faso Case Study

Characterization

Unlike the previous two, this case study focuses on strategies formulated at the national level, drawn largely from a series of technical and policy proposals (Mokwunye et al., 1996; De Jager & Smaling, 1996; Bikienga, 1997; Dembele, 1996). The Central or Mossi Plateau of Burkina Faso is a semiarid, low-potential area typical of the Sudanian belt of Sahelian West Africa. It is characterized by low (600-800 mm yr^{-1}) and highly variable rainfall, naturally infertile sandy Alfisols very low in N, P, and SOM, high soil erosion risk, and cropping systems based on low yields of sorghum *[Sorghum bicolor* (L.) Moench] and pearl millet *[Pennisetum* glaucum (L.) R. Br.] in between scattered parkland trees. There is low (20 people km^{-2}) but increasing population density, unavailability of fertilizers to smallholders, and insecure land ownership by individuals, while tree tenure is held by the government (Sanders et al., 1996). There is a relatively large PR deposit (Kodjari) under production for local use. About 10% of the country's land under cultivation has stone lines, diguettes, or other soil erosion control devices. Fertilizer use is largely limited to cotton *(Gossypium hirsutum* L.) growing areas run by parastatals (Bikienga, 1997).

Extensive on-station and on-farm research shows that P deficiency must be overcome before N responses can be realized. The reactivity of the Kodjari PR is low. It is not recommended for direct application, but it could be used with partial acidulation (Bationo & Mokwunye, 1991). Even with the low pH values of most soils (4.5 to 4.8), 2 to 3 yr are required to achieve full crop responses to this PR. Solubilizing Kodjari PR with organic acids derived from composts, however appears promising (Lompo, 1993).

Action Plan

The Burkina Faso government eliminated fertilizer subsidies in 1987. In 1995, a multidisciplinary Soil Fertility Management Unit (Unite da Gestion pour la Fertilite des Sols) was established at the cabinet level to design strategies and action plans to replenish soil fertility in the most depleted areas with a combination of fertilizers, improved germplasm, and the development of inputs and outputs markets (Dembele, 1996). Nationwide sensitization workshops enabled the Soil Fertility Management Unit to increase awareness of soil-fertility depletion as well as to combine efforts to improve the availability of nutrient inputs along with the marketing of farm products. The basic strategy is to use Kodjari PR to correct P deficiency as a one-time capital investment paid by the government via donors. This calls for a basal application of 400 to 600 kg ha^{-1} of Kodjari PR (12% P), which is equivalent to 48 to 72 kg P ha^{-1}, supplemented by annual maintenance PR applications of 12 to 24 kg P ha^{-1} and urea (Bikienga, 1997).

Market research shows that the private sector is reluctant to sell fertilizers on credit to smallholder cereal producers due to high investment risk from drought (Dembele, 1996). Therefore, the government feels it must take over input distribution. The plan also includes improving the technical knowledge about fertilization by private distributors and increasing the role farmer organizations play in fertilizer and cereal trade.

A full country-wide replenishment, including maintenance doses, requires 4.3 million t of Kodjari PR ore annually. The current estimate is that Kodjari PR deposits can supply that rate for 60 years (Bikienga, 1997). Furthermore, priority is to be given to the 700 000 farmers that have invested in soil erosion control and compost pits, and those that grow grain legumes in rotation with cereal crops. The plan is to be implemented by farmer associations that focus on women. Bikienga (1997) calculates the cost of Kodjari PR at farm gate to be US$ 150 t^{-1} similar to the cost of Minjingu PR in western Kenya. Total development costs for 5 yr, including refurbishing the current Kodjari PR production site, purchasing 90 000 t of PR, 3000 village demonstrations, training, and monitoring are estimated to be about US$ 25 million (calculated from Bikienga, 1997).

There are no specific provisions in this plan for organic inputs, except for growing grain legume crops in rotation, which as discussed earlier is not a realistic way to replenishing N. Phospho-composts appear to be a more feasible option (Lompo, 1993), but their costs need to be fully assessed. Other options that may be considered are leguminous tree fallows capable of growing during the dry season, like in Zambia and Kenya, or biomass transfers like in Kenya. Both options need to be researched. The woody fallow species must be adapted to the climate and soil stresses of the Sahel. Research near Bamako, Mali indicates that gliricidia *[Gliricidia sepium* (Jacq.) Walp.] fodder banks produce significant leaf biomass, about 3 t ha^{-1} yr^{-1} of dry matter (ICRAF, 1995), with a potential accumulation of 60 to 90 kg N ha^{-1} yr^{1}.

Profitability

A World Bank-sponsored PR feasibility study based on data from the central and northern regions of Burkina Faso shows a NPV of US$ 396 ha^{-1} for the local PR, using a 20% discount rate for private benefits, 10% for national benefits, and 2% for global benefits (World Bank, 1996, unpublished study). At low rates of application, imported soluble P fertilizers are more profitable than Kodjari PR. In response to this finding a better option might be to use the low-reactive PR as the basal application and lower rates of superphosphate as yearly applications. It is relevant to note that this study did not include the use of organic inputs. This action plan is still in its formative stage and unlike the previous one, no pilot trials have been conducted at the time of this writing.

ENABLING POLICIES

The three different case studies show that various fertility replenishment strategies are profitable. Despite this, smallholder farmers face daunting constraints to fertilizer use (Runge-Metzger, 1995). In the long-run, the alleviation of these constraints through improved government policies will provide farmers more incentives to undertake soil replenishment investment.

The soil-fertility replenishment approach should emphasize the provision of truly public goods such as infrastructure and improved technologies, the removal of distorting incentives in agricultural input and output markets, and the encouragement of rural credit markets. The provision of credit at reasonable interest rates is viewed as particularly critical because investment in nutrient replenishment will be profitable in most cases, despite the poor marketing conditions of many rural areas.

These policies may not, however, address the urgent short-term needs of resource-poor farmers. One short-run strategy might include the improvement of the availability and delivery of P fertilizers and both organic and inorganic N sources to farmers. This may take the form of facilitating importers in fertilizer acquisition, providing storage facilities, provision of germplasm for fallows and biomass transfer, and extending credit to wholesalers or retailers. This also should include better training of extension agents on adapting blanket nutrient input recommendations to specific farmer needs and nursery development for providing germplasm of the organic sources; however, improving fertilizer supply is not sufficient to encourage the uptake of P by farmers as demand is influenced by price and capital.

A short-term replenishment strategy must therefore also consider either the options of increasing credit to farmers or cost-sharing. If capital is truly the major constraint and P replenishment has strong residual effects, then one presumes that farmers would have sufficient incentives and profits with which to reinvest in maintenance nutrient inputs. In this case, the level of government intervention could be phased out, especially as the longer-term enabling policy changes begin to take effect. Even in the long-run, however, there can be some scope for direct government intervention in P fertilizer and germplasm delivery if social returns from replenishment significantly exceed private returns to fanners under liberalized market conditions. In this case, the level of farmer investment in P fertilizers and tree nurseries will be less than optimal from society's point of view.

Credit for the Poor

Local access to credit at reasonable interest rates will be needed to finance costs that do not fall in the category of natural capital investments (improved seed of food crops and high-value plants, integrated pest management, N fertilizers, and maintenance fertilization of other nutrients). Mohammed Yunus, a banker, created the Grameen Bank in Bangladesh based on the explicit goal of alleviating poverty. It gives small loans at market interest rates. In the process Yunus broke several banking rules: (i) the less money a person has, the more credit worthy that person and (ii) wage employment is less important than the possibility of becoming self employed. The best loan performers are rural women, which constitute 94% of the 2.1 million Grameen Bank's borrowers. The Bank has a loan recovery rate of more than 90%; it is now known as the *Bank of the Formerly Poor* (M. Yunus, speech at the World Food Prize Symposium, Des Moines, Iowa, 18 October 1996).

Peer pressure is a key component of the Grameen Bank's success. Out of a group of borrowers, the second two borrowers receive their loans only after the first two repay their loans, and the group leader is usually last in the group to receive a loan (Gladwin et al., 1997, this publication). Microcredit facilities, following the Grameen Bank model are now being used in Sasakawa Global 2000 projects in Ethiopia and Benin for loans up to 50% of the cost of inputs, with recovery rates of 90% or higher (Quinones & Takele Gebre, 1996). This is certainly a model to follow in order to finance N fertilizers, hybrid seed, and other recurring costs for recapitalized soils. Furthermore, a recapitalized soil is likely to reduce the riskiness of a farmer in the eyes of a creditor.

Cost-Sharing

Based on the concept of the different kinds of capital described by Serageldin (1995), we concluded that soil fertility is most definitely a form of natural capital. Benefits to farmers will be large. As such, they should be expected to contribute land, labor, and even capital towards the replenishment of their soils. Capital constraints, however, may prohibit significant farmer investment in P. Government intervention to promote credit is called for. If societal benefits of a regional P-replenishment project exceed the costs, cost-sharing mechanisms may be warranted,

Izac (1997, this publication) identifies organic inputs and PR as two types of natural capital that can be considered as capital investments, because they generate international public goods out of positive environmental externalities. Capital investments are different from subsidies in that they have a profit expectation in the long-term—an explicit return on the investment—while subsidies are short-term removals of constraints. Therefore, it may be advisable for society to assume some of the costs involved in moving farmers from unsustainable to sustainable production systems, in recognition of the socially and environmentally desirable externalities involved (Cleaver & Schreiber, 1994; Izac, 1997, this publication).

In order for soil-fertility investments to have national or global benefits, they must be adopted at a large scale. Soil-fertility investments in only individual scattered farms will not provide national or global benefits. Action plans, such as the one for Burkina Faso (Bikienga, 1997) start gradually but are clearly aimed at recapitalizing large parts of the countryside.

We, therefore, suggest that national and global societies invest in actions that increase the soil's nutrient capital in the long term. This means investing in large, one-time corrective applications of P fertilizers and in organic inputs that build up N, P, and C in the SOM (Izac, 1997, this publication). It also means *not* investing in N fertilizers as long as they do not build soil nutrient capital under present smallholder conditions, which do not include accompanying organic inputs.

The efficiency argument against subsidies (see Gladwin et al., 1997, this publication) is made irrelevant by the cost-sharing just described, when economic and environmental externalities are taken into account. Izac (1997, this publication) describes several long-standing cost sharing schemes between farmers and governments in developed countries, including assistance to farmers for planting trees to meet soil conservation objectives in the USA. Certainly something similar could be applied in tropical developing countries.

CONCLUSIONS

Combinations of P fertilizers and organic inputs can replenish soil nutrient stocks in Africa and restore service flows approaching their original levels. Such restoration is in essence a long-term investment in the rebuilding of a country's stock of natural capital. We believe that the way forward is *a cost-shared initial capital investment to purchase P fertilizer and germplasm to grow organic inputs combined with effective micro-credit for recurring costs such as N fertilizers and hybrid seed.*

Given the positive social and environmental externalities associated with soil-fertility replenishment, an equitable cost-sharing mechanism can be developed and implemented, similar to existing ones in countries belonging to the Organization for Economic Co-operation and Development (OECD) that deal with positive environmental externalities (Izac, 1997, this publication). Cost sharing of the capital investments should be done on the basis of whoever benefits should pay. Subsidies, in our view, have a limited role to play. Being a *one-time only* investment, some of the dark sides of subsidies such as continuity and dependency are not likely to play a major role.

Phosphate resources are certainly abundant in Africa. There is no question as to the essential role of P inputs regardless of whether P is replenished via direct applications of PR, combinations of PR with organic inputs to help its solubility, or via superphosphates.

One of the main arguments against the use of organic N inputs is their low N concentration, in comparison with inorganic N fertilizers; however, when a leguminous fallow grown during the dry season or when no crops are in the field, can accumulate 100 to 200 kg N ha^{-1} though BNF or deep nitrate capture, the low concentration argument becomes irrelevant. Although this in situ N production is not free, as it requires labor inputs, it certainly does not require significant cash inputs or entail transport costs. The biological approach to N replenishment must be viewed from a different perspective, now that short-term improved leguminous fallows are becoming a reality in Africa.

A soil-fertility strategy for Africa must effectively address well-known constraints in a novel way. The international donor community is asking much of smallholder African farmers: Borrow money at 20% interest rates, work for about US$ 1 per day, not to benefit from subsidies, and become effective stewards of natural resources amidst poor transport infrastructure and weak support institutions. This is in sharp contrast to the situation faced by farmers in the North, who borrow money at low interest rates, have higher opportunity cost of labor, continue to benefit from deeply institutionalized subsidies (e.g., for fertilizer, cereals, milk) and many cost-sharing schemes (when positive environmental externalities exist), and rely on a superb transport and information infrastructure. An enabling policy environment to the farming sector in developed countries is no justification for transferring the same elsewhere; but African farmers could really use a break in replenishing one of their most basic of natural resources—the soil.

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2 Soil Fertility in Africa Is at Stake

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ABSTRACT

Soil fertility in Africa is under pressure as an increasing number of fanners attempt to make a living based on what the land can offer to growing plants. Studies in Africa from about 1989 have focused on different spatial scales, i.e., subcontinental, subnational, and farm. This chapter reviews the results obtained at these three levels and compares methodologies and implications. For N, annual depletion was recorded at all levels at rates of 22 kg ha^{-1} (sub-Saharan Africa), 112 kg ha^{-1} (Kisii District, Kenya), and 71 kg ha^{-1} (average for 26 farms in Kisii, Kakamega, and Embu Districts). If the soil nutrient balance is to become a suitable land quality indicator for wider use as a policy instrument, increased sophistication is required, including data on soil nutrient stocks and availability. The advantage of the nutrient balance approach over traditional rate-response research on fertilizers is that it includes all possible nutrient flows at the spatial scales discussed. A drawback, however, is the lack of hard data on flows that are difficult to measure (leaching, gaseous losses, and erosion), and the fact that the balance comprises several inputs minus the sum of several outputs. Nonetheless, the message comes out clearly that improved soil nutrient management is crucial for maintaining and improving soil productivity in Africa.

Soil fertility is not a static feature. On the contrary, it changes constantly and its direction (accumulation or depletion) is determined by the interplay between physical, chemical, biological, and anthropogenic processes. This dynamism also is reflected in terminology such as nutrient cycles, budgets, or balances, referring to inputs and outputs in natural ecosystems and managed agroecosystems, to which nutrients are added and from which nutrients are removed. As the world

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population keeps growing, balanced ecosystems are on the decrease and nutrient ledgers all over the world have become increasingly imbalanced. Great nutrient surpluses and subsequent undesirable emissions to the environment now occur in many farming systems in temperate regions, and increasing soil-nutrient depletion and crop yield declines are reported in the tropics, particularly in rainfed sub-Saharan Africa (hereafter referred to as Africa; Pieri, 1989; Stoorvogel & Smaling, 1990; Van der Pol, 1992). In rural appraisals, an increasing number of African farmers indeed mention soil fertility decline as a major constraint to farming.

The yield-increasing effect of mineral fertilizers has long been the main nutrient management technology researched, amongst others, by the numerous though poorly documented rate-response trials of the FAO Fertilizer Programme. Presently, however, land-use planning approaches are aimed at integrated nutrient management (INM), perceived here as the best combination of available nutrient management technologies, i.e., those that suit local biophysical conditions and are economically attractive and socially relevant (Smaling et al., 1996). FAO has also adopted this philosophy and now runs an Integrated Plant Nutrition Programme in different parts of the tropics. Integrated nutrient management technologies can be nutrient saving, such as in controlling erosion and recycling crop residues, manure, and other biomass, or nutrient adding, such as in applying mineral fertilizers and importing feedstuffs for livestock. Some practices strive at both, such as improved fallowing and agroforestry. As each agroecological zone has its potentials and limitations, the number of relevant INM options is site specific. In the eastern African highlands, for example, with reliable rainfall and deep, relatively fertile soils, more options are available to safeguard productivity than in semiarid West Africa, with less and erratic rainfall and sandy, often shallow soils. Of late, the nutrient balance and INM have been adopted by the World Bank as key to the debate on sustainable agricultural systems in the tropics. As a consequence, work is under way to turn the nutrient balance into a land quality indicator (Pieri et al., 1995).

Nutrient balances apply to different spatial scales. To visualize this, one should build an imaginary fence around the system of interest. For the farm system, for example, this fence surrounds the entire farm holding. The floor runs just below the root zone of plant species that grow in the particular farming systems, whereas the roof stretches over the top of the tallest species. Now one can determine whether a nutrient flow is really an input or an output, i.e., crossing this fence, or whether one deals with an internal flow inside the fence. Concentrates purchased to feed stalled cattle, for example, are nutrient inputs to the farm, but roughage such as napier grass *(Pennisetum purpureum* Schumach.) or silage maize *(Zea mays* L.) grown within the farm is no input at this level. It is, however, an output for the plot where these plants were grown, and an input to the stable, which are both compartments of the farm. Similarly, soil that leaves the farm through water erosion represents a nutrient output, but eroded soil from upper slopes may enter the same farm and become an input. Eroded soil reaching rivers may end up in the ocean and is also then an output at the country scale. Another percentage may, however, be deposited as sediment in flood plains in the lower parts of the river basin. This is the case in large parts of agricultural China, where soils in the plains remain productive by virtue of erosion in the mountains. At the level of the soil solution, the nutrient balance in fact represents plant-nutrient availability. Any applied P fertilizer is an input to the farm and the soil, but a large part may be strongly sorbed by sesquioxides or precipitated, and as such it is no immediate input to the soil solution. In other words, nutrient availability reflects a nutrient balance at soil-solution level, modified by the process groups mineralization-immobilization (highly important for N, S, and often P), sorption-desorption (highly important for P and cations) and weathering-precipitation (highly important for micronutrients and P).

In this chapter, results are summarized from earlier and ongoing nutrient balance studies in Africa at subcontinental, subnational, farm, and field levels. Differences in interpretation among these studies are discussed and future avenues for nutrient-balance research given.

CALCULATING NUTRIENT BALANCE AT DIFFERENT SPATIAL SCALES

Subcontinental Scale

In the late 1980s, FAO replaced its fertilizer-driven philosophy by an INM approach, which triggered a debate on high versus low external input farming. In this context, FAO commissioned a study on nutrient balances in agricultural systems in Africa, with the aim of creating awareness on not just the state of soil fertility in the subcontinent but also its dynamics. The nutrient balance study for 38 African countries (Stoorvogel & Smaling, 1990; Stoorvogel et al., 1993) involved partitioning the continent into rainfed cultivated, irrigated, and fallow land, for which FAO provided hectarages and yields. Rainfed land was further divided on the basis of the length of the growing period and the soil map of Africa, at a scale of 1:5 000 000 (FAO/UNESCO, 1977). The basic spatial unit was the land-use system, for which five nutrient inputs and five nutrient outputs were calculated or estimated (Table 2-1). For this exercise, many country statistics, maps, reports, and literature were scrutinized. A detailed account of the information garnered and interpreted is annexed to the main document by Stoorvogel and Smaling (1990).

The amount of data available to calculate the five inputs (IN 1 to 5) and the five outputs (OUT 1 to 5; Table 2-1) varied largely between and within countries. As a consequence, much available detail had to be dropped and discrete ratings developed for variables that normally represent a continuum. Also, average values were used for properties that showed wide ranges, such as crop-nutrient contents. Quantitative information on atmospheric deposition, leaching, and gaseous losses was very scarce. Instead of going by educated guesses, transfer functions were built (Bouma & Van Lanen, 1987; Wagenet et al., 1991). These are regression equations, in which the nutrient flow is explained by parameters that are easy to measure. For leaching, for example, the equations represent the best fit for a series of point data on leaching, which were accompanied by such building

Table 2-1. Nutrient inputs and outputs calculated in continental and district studies.

Nutrient inputs	
INI	Mineral fertilizers
IN2	Organic inputs (manure, feeds, waste)
IN3	Atmospheric deposition in rain and dust
IN4	Biological nitrogen fixation
IN5	Sedimentation by irrigation and natural flooding
Nutrient outputs	
OUT 1	Harvested products
OUT 2	Crop residue removal
OUT 3	Solute leaching
OUT 4	Gaseous losses
OUT 5	Runoff and erosion

blocks as rainfall, soil fertility class, and use of fertilizer and manure. Soil fertility classes were merely rated low (1), moderate (2), and high (3) on the basis of soil taxonomy (sub)orders. Mollisols, for example, were ranked 3, whereas Psamments were ranked 1. For erosion, quantitative information on soil loss was amply available, but its translation into nutrient losses was seldom studied. Moreover, the studies were often done at the miniplot level, the results of which cannot be linearly scaled up to the watershed.

The results can be portrayed per land-use system, per agroecological zone, per country, and also per nutrient for the entire continent. The average N, P, and K balances for Africa were -22, —2.5, and -15 kg ha^{-1} yr^{-1}, respectively. Nutrients exported in harvested products, in runoff, and in eroding sediments were high and caused the balances to be negative. The implication of the figure is that on average, soils in Africa must supply 22 kg N ha^{-1} each year to balance the ledger, leading to a decline of the N stocks. Figure 2-1 shows the results averaged for each country. There are countries with near-equilibrium nutrient balances and those with high nutrient depletion.

Nutrient depletion is most intense in East Africa, next in coastal West Africa and southern Africa, and least intensive in the Sahelian Belt and Central Africa (Table 2-2). In East Africa, major faulting and volcanic activity have produced red fertile soils derived from basalt that are generally known as Nitisols (FAO, 1988)—rhodic groups and subgroups of Alfisols and Oxisols (Soil Survey Staff, 1992)—and Vertisols at low landscape positions. High nutrient depletion is due to high outputs of nutrients in harvested products and erosion and also in the relatively high inherent fertility of the soils. Coastal West African countries are dominated by Alfisols of moderate fertility, in both humid forest and moist savanna regions. Southern Africa also is dominated by Alfisols, many of which are sandy and of low inherent fertility. Often associated with these are Vertisols derived from basalt that are intensively cultivated as dambo gardens. The Sahelian belt—from Senegal to Somalia—is characterized by sandy Alfisols and Entisols, often of extremely low fertility, and irrigated Vertisols and Entisols adjacent to major rivers. Central Africa is characterized by infertile, acid Ultisols, Oxisols, and Entisols in both forested and savanna regions.

Nutrient depletion (kg ha^{-1} yr $^{-1}$)

	N	P	K
Low	< 10	< 1.7	< 8.3
Moderate	10 to 20	1.7 to 3.5	8.3 to 16.6
High	20 to 40	3.5 to 6.6	16.6 to 33.2
Very high	≥ 40	≥ 6.6	≥ 33.2

Fig. 2-1. Classification of soil nutrient balances for the arable land of sub-Saharan Africa (adapted from Stoorvogel & Smaling, 1990).

Table 2-2. Estimated nutrient-depletion rates in cultivated land in subregions of sub-Saharan Africa in 1983, excluding South Africa.t

	SubregionJ					
Parameter	East African Highlands	Coastal West Africa	Southern Africa	Sahelian Belt	Central Africa	Total sub-Saharan Africa
Cultivated land (million ha)	39	63	24	55	20	201
Depletion rate, (kg ha"' yr–1)						
N	36	27	20	11	10	22
P	5	3	2	2	1	2.5
K	25	18	14	8	8	15
Total depletion (million t ha-1 yr1)						
N	1.38	1.70	0.48	0.63	0.21	4.40
P	0.19	0.19	0.06	0.09	0.02	0.55
K	0.97	1.14	0.32	0.45	0.15	3.03

† Source, Stoorvogel and Smaling (1990).

‡ Countries included in each region as follows East African Highlands: Burundi, Ethiopia, Kenya, Madagascar, Rwanda, Tanzania, and Uganda. Coastal West Africa: Benin, Cameroon, Cote d'lvoire, Ghana, Guinea, Liberia, Nigeria, Sierra Leone, and Togo. Southern Africa: Angola, Botswana, Lesotho, Malawi, Mozambique, Swaziland, Zambia, and Zimbabwe. Sahelian Belt: Burkina Faso, Chad, The Gambia, Mali, Mauritania, Niger, Senegal, Somalia, and Sudan. Central Africa: Central African Republic, the two Congos, and Gabon.

Sub national Scale

The subcontinental scale and uneven data availability implicitly brought about a considerable amount of generalization, simplification, and aggregation. As a follow-up, similar studies were done at subnational scales, i.e., in the 2200-km^2 subhumid Kisii District in Kenya (Smaling et al., 1993) and in the 12 230-km^2 semi-arid region of southern Mali (Van der Pol, 1992). Primary data were available on climate, soils, land use, mineral fertilizers, farmyard manure, crop yields and residues and their nutrient content, and to a lesser extent on erosion. Kisii soils are predominantly well drained, very deep, and rich in nutrients (Mollisols, Luvisols), with the exception of P. Mean annual rainfall ranges between 1350 and 2050 mm. Major food crops in the district are maize and bean *(Phaseolus vulgaris* L.), often grown in association. Major cash crops include tea *[Camellia sinensis* (L.) Kuntze], coffee *(Coffea arabica* L.), and pyrethrum *[Chrysanthemum cinerariaefolium* (Trev.) Bocc.]. Most farm holdings in addition comprise small improved pastures for livestock. Less than 5% of the land is left fallow during a year. In southern Mali, millet *[Pennisetum glaucum* (L.) R. Br.; 20% of arable land], sorghum *[Sorghum bicolor* (L.) Moench; 17% of arable land], and cotton *(Gossypium hirsutum* L.; 15% of arable land) are the major crops of the region. Smaller percentages of maize and groundnut *(Arachis hypogaea* L.) are grown. Approximately 29% of the arable land is left fallow in a year.

Calculations revealed that annual nutrient depletion in Kisii District was 112 kg N ha^{-1}, 2.5 kg P ha^{-1}, and 70 kg K ha^{-1} (Table 2-3), whereas in southern Mali the values were 25 kg N ha^{-1}, 0 kg P ha^{-1}, and 20 kg K ha"1 (Table *2-X).* In

Table 2-3. Nutrient budget in Kisii District, Kenya, t

Element	IN 1	IN 2	IN 3	IN 4	OUT 1	OUT 2	OUT 3	OUT 4	OUT 5	Total
					kg ha^{-1} yr^{-1}					
N	17	24	6	8	55	6	41	28	37	−112
P	12	5	1		10	1	0		10	−3
K	2	25	4		43	13	9		36	−70

† Source, Smaling et al. (1993).

Table 2–4. Nutrient budget in southern Mali.†

Element	IN 1	IN 2	IN 3	IN 4	OUT 1 + 2	OUT 3	OUT 4	OUT 5	Total
					kg ha^{-1} yr^{-1}				
N	7	3	10	3	23	4	12	9	−25
P	2	1	2		3	0		2	0
K	2	3	6		14	4		13	−20

t Source, Van der Pol (1992).

Kisii, removal of nutrients in the harvested product (OUT 1) was the strongest contributor to the negative balance, followed by runoff and erosion and, for N, leaching. Use of mineral fertilizers and manure in Mali is much less than in Kenya, but crop production is also lower, reflected in lower values of the output of aboveground crop parts (OUT 1). Because of lower rainfall and flatter topography, losses from leaching, denitrification, and erosion also were smaller in Mali.

At the crop level, conclusions drawn from the Kisii study revealed that pyrethrum is the big nutrient miner (-147 kg N, -24 kg P, -96 kg K ha^{-1} yr^{-1}), whereas tea has the most favorable nutrient balance (-67 kg N, +6 kg P, -30 kg K ha^{-1} yr^{-1}). Pyrethrum receives little mineral or organic fertilizer, has a high nutrient content per unit of harvested product and protects the surface poorly against erosion. Tea, however, receives substantial amounts of mineral fertilizer and offers good protection to the topsoil. In southern Mali, millet is the big nutrient miner (-47 kg N, -3 kg P, -37 kg K ha^{-1} yr^{-1}), whereas cotton has the most favorable nutrient balance (-21 kg N, +7 kg P, -9 kg K ha^{-1} yr^{-1}). Millet receives virtually no mineral or organic fertilizer and has a high nutrient content per unit of harvested product as compared with sorghum. Cotton, however, receives substantial amounts of fertilizer.

Farm and Field Scale

The subcontinental and subnational studies revealed that N and P, on average, are moderately to strongly mined. In Kisii District, soils are still rich enough to produce high agricultural output. But for how long? And how will farmers be told not to go for high crop yields when they can obtain them? Should farmers apply N fertilizer when the N balance is as negative as -112 kg ha^{-1}? These questions were posed by many interested parties after publication of the subcontinental and subnational studies, and they triggered the development of a proposal for a nutrient monitoring programme (NUTMON) at the farm scale (Smaling & Fresco, 1993; Smaling et al., 1996).

In 1995, a Rockefeller Foundation-sponsored NUTMON pilot project started in 26 farms in three agroecologically and ethnically different districts in Kenya (Kisii, Kakamega, and Embu). The initial phase included interpretation of satellite images and identification of more or less homogenous land-use zones. In each zone, rural appraisals were then held, which led to the identification of characteristic farm types for each land-use zone and the subsequent selection of pilot farms. For each farm, an initial inventory was done on household composition, farm and field architecture, agricultural activities, and nutrient stocks. This was then followed by monthly monitoring of farm management activities related to nutrient flows and related economic factors (De Jager et al., 1998b).

Results so far indicate an average negative N balance of -71 kg ha^{-1} for the three districts (Van den Bosch et al., 1998); however, if one just looks at the flows that are managed directly by the farmer (mineral and organic fertilizers, and harvested crops and residues leaving the farm), the annual N balances are positive (10, 35, and 46 kg N ha^{-1} for Kisii, Kakamega, and Embu Districts, respectively). Phosphorus and K balances were close to equilibrium. It appeared that input through manure derived from communal lands, where animals are grazing during daytime, is an important nutrient input at the farm level. The virtual absence of these communal lands in Kisii explains the lower N balance value. One major methodological constraint was that some flows were actually measured, whereas others such as leaching and gaseous losses were estimated. Yet they influence the value of the balance very much.

Relations also have been established between economic performance indicators, the socioeconomic environment, farm management practices, and nutrient balances. It was found that net farm income shows no relation to the nutrient balance (De Jager et al., 1998a). A high degree of market orientation, however, correlated well and negatively with the N and K balance. The market-oriented farms located in the densely populated areas and characterized by intensive crop and livestock activities import nutrients through fertilizers and animal feeds, but the amount is insufficient to compensate for the outflow through marketed products, leaching, and erosion. Subsistence farms in the less populated areas (drier parts of Kakamega and Embu) have a relatively successful strategy to concentrate nutrients through grazing of cattle in communal lands. Off-farm income also proved very important for households to survive. Without this source of income, 54% of the farms in the sample would be below what the World Bank considers to be the poverty line. The replacement costs of mined nutrients amounted up to 35% of the average net farm income.

At the crop and field level, cash crops such as tea and coffee realized higher gross margins and considerably lower nutrient mining levels than the major food crops, maize, and beans. Application of sufficient nutrients to food crops apparently is not viable in the current economic environment (De Jager et al., 1998a).

DIFFERENT SCALES: DIFFERENT CONCLUSIONS

Comparing Subcontinental and Subnational Scales

The Kisii District study yielded nutrient loss values of -112 kg N and -3 kg P ha^{-1} yr^{-1}. In the subcontinental study, the extrapolated nutrient balance for Kisii District would have been -75 kg N and -5 kg P ha^{-1} yr—1. In the latter study, all soils would have been in Fertility Class 2 (moderate), characterized by 1 g N kg^{-1} soil and 0.2 g P kg^{-1} soil. In reality, however, the soils have a higher N content, which could be adequately covered in the district study. Pyrethrum turned out to be the major nutrient miner in the district study, but it was not included in the supranational study because it lacked importance at mat scale. Hence, the differences between the results of the two studies are differences in resolution.

Comparing Subnational and Farm Scales

In the NUTMON pilot, farm-determined nutrient balances for Kisii were -102 kg N, -2 kg P, and -34 kg K ha^{-1} yr^{-1}, which compare well with the subnational estimates (Van den Bosch et al., 1998). Variation around the mean, however, was considerable. Nutrient stocks used in the subnational study were average values for land units on a 1:100 000-scale soil map for Kisii District (Smaling et al., 1993). The six farms in Kisii District had total N concentration between 1.5 and 4.6 g kg^{-1} soil and total P concentration of 0.9 to 1.3 g kg^{-1} soil.

Comparing Farm and Enterprise Scales

Nutrient stocks of individual plots within farms and village territories can differ considerably. Reasons range from differences in soil texture, land-use and fallow history to microclimatic differences. Smallholder farmers exploit microvariability, because for each weather condition, there are pieces of land where crops perform well (Brouwer et al., 1993). Hence, farm and field heterogeneity is often regarded as an asset by those who are resource poor and risk averse, their goal being food security rather than bumper harvests. An example of taking advantage of heterogeneity is the use of termite mounds, representing spots of relatively high fertility. Another striking example of farm-level variation is in the ring management systems in semiarid West Africa, where inner circles near the farms and village are much more intensively used and managed than outer rings (Prudencio, 1993; Sedogo, 1993). Of the three subsystems shown in Table 2-5, the homestead fields represent the plots just around the homestead, and receive substantial amounts of nutrients from animal manure and household waste. As a consequence, soil productivity in this part of the farm remains at a relatively high level.

In the NUTMON pilot project, it became clear that cash crop and food crop plots are treated quite differently as regards nutrient flows (De Jager et al., 1998b). The role of livestock in the farming system and the amount of manure reaching certain plots largely determines within-farm differences in nutrient stocks and flows (Mohamed-Saleem, 1998; Van den Bosch et al., 1998).

Table 2-5. Nutrient stocks of different subsystems in a typical upland farm in the Sudan-savanna zone of West Africa.

Farm subsystem	pH in H_2O	Organic C	Total N	Extractable P	Exchangeable K
		g kg^{-1}†		mg kg^{-1}	mmol$_c$ kg^{-1}
Homestead fields	6.7-8.3	11-22	0.9-1.8	20-220	4-24
Village fields	5.7-7.0	5-10	0.5-0.9	13-16	4-11
Bush fields	5.7-6.2	2-5	0.2-0.5	5-16	0.6-1

† Source, Sedogo (1993).

NEED FOR INDICATORS AS A MEASURE OF PRODUCTIVITY AND SUSTAINABILITY

The studies discussed in this chapter contributed to the shortlisting of nutrient balance as a land-quality indicator in a World Bank initiative to capture the current quality of land, the pressures exerted on it, and societal responses (Pieri et al., 1995). Does nutrient balance qualify as such? Perhaps, but it may be wise to first list the many constraints that may preclude its usefulness and the opportunities involved.

Constraints

Farmers continue to deplete soil nutrients as long as the land provides them sufficient food and cash to make it through the year. In Kisii District, for example, gross nutrient mining was observed, but as soil fertility is still rather high, crop production was also rather high. In other words, as long as the soil is able to buffer the negative balances before reaching low levels of nutrient availability, farmers will not notice changing soil fertility the next year. The nutrient balance alone is therefore not sufficient as an indicator of soil productivity. It needs to be linked with soil nutrient stocks, either with the total stock or with the stock of available nutrients. The latter may be defined as the nutrients that are present in the soil solution at the beginning of the growing season or will enter the soil solution during the season.

Not all inputs and outputs are easily measured. Determining inputs by mineral fertilizers may require a quick look at district statistics, and yield estimates may just require some ground-truth measurements. For leaching and gaseous losses, however, transfer functions are needed, which are made up of different parameters with values that are often obtained from secondary sources, and hence their values are less reliable than those of nutrients in crop products.

A nutrient balance value may contain considerable error because it reflects the aggregation of five inputs and five outputs. The sheer lack of certain categories of primary data in the tropics makes it difficult to put the nutrient balance concept into operation. There are no examples of benchmark sites where all 10 parameters of Table 2-1 have been measured simultaneously over sufficiently long periods.

For the continental, national, and district studies, input data for the nutrient balance are mostly derived from subdistrict statistics and are thus already aggre-

Table 2-6. Ratios of easy-to-measure nutrient flows with the sums of all flows.

	(IN 1 + IN 2)/ (total inputs)		(OUT 1 + OUT 2)/ (total outputs)		(Balance 1 + 2)/ (total balance)	
Element	Kisii	Mali	Kisii	Mali	Kisii	Mali
N	0.75	0.43	0.37	0.48	0.18	0.52
P	0.94	0.60	0.52	0.60	-2.00	1.00
K	0.87	0.45	0.55	0.45	0.41	0.45

gated to some extent (soil maps, district statistics, national fertilizer-use statistics). Moreover, the loss of resolution and of relevant human-induced and natural spatial variability tends to produce average figures and trends without any information on standard deviation.

Opportunities

For the nutrient balance to become a meaningful land-quality indicator, it is necessary to develop a quality index, relating nutrient balance to nutrient stocks in one way or another. The concept of stocks and flows is in line with economists' style of budgeting and may help in bridging gaps between disciplines. Moreover, it will be possible to estimate how long nutrient mining in a given land-use system can continue unabated.

The most straightforward approach would be the use of nutrient balance and nutrient stocks where both include all nutrients, irrespective of their availability. The strength of such an index is that it provides information on the long-term fate of the land and not just of the next crop. A disadvantage is that it is not directly related to the nutrients that are immediately available and hence not to crop growth. Another drawback is the difficulty to assess the values of the nutrient balance, certainly in low-data environments. An index consisting only of flows that can be easily determined would have much more practical meaning. These flows are IN 1 and IN 2 (mineral and organic fertilizers), and OUT 1 and OUT 2 (removed biomass in harvest and crop residues). The values of these four flows are all strongly human influenced and directly reflect the farm households' allocation of capital and labor as well as income generation and food security strategies.

Disadvantages are that potentially important flows are ignored. This would not matter if the proportions of the various INs and OUTs were little affected by the type of agrosystem. It is obvious from Table 2-6 that neither IN 1 + IN 2 nor OUT 1 + OUT 2 is a constant portion of the total input or output. Dividing the truncated balance by the total balance (last two columns of Table 2-6) may even lead to negative values (e.g., P in Kisii). Similar results as in Table 2-6 were found for the data by Stoorvogel and Smaling (1990), implying that the use of only INs 1 and 2, and OUTs 1 and 2 instead of all INs and OUTs does not offer good prospects. Nevertheless, the ratio (IN 1 + IN 2)/(total inputs) presents interesting information, for it indicates the degree of human involvement in nutrient supply. The ratio (OUT 1 + OUT 2)/(total outputs) indicates which fraction of the outputs can be seen as useful.

In the quest for a land-quality indicator for nutrients that is also directly related to yield, the appropriate flows of available nutrients must first be identified. This is simple for the outputs: OUTs 1 through 4 refer to available nutrients, while OUT 5 (erosion) also refers to nutrients that are not immediately available because they are present in solid organic and inorganic particles, in addition to available nutrients. For the inputs the situation is more complex. The nutrients of IN 4 are plant available. Those of IN 3 are directly available as far as wet deposition is concerned (estimated at 50%), whereas those in dry deposition (the other 50%) are in an unavailable form. Those of IN 5 are not available when just considering sedimentation and not run-on. The nutrients of IN 1 and IN 2 are partly or entirely in an available form. N and K in chemical fertilizers and K in organic fertilizers usually can be considered as available. Water-soluble P fertilizers and organic fertilizers have about the same fraction of available P; it is often set at 0.1, but it varies between 0.05 and 0.2 depending on soil properties and weather conditions. The availability of N in organic fertilizers is affected by weather conditions, length of growth season, and type of manure. An often-used default value is 0.4. With these assumptions, the following formulas were applied to estimate the balance of INs and OUTS of available nutrients:

for N: (IN 1 + 0.4 IN 2 + IN 3 + IN 4) - (OUTs 1 to 4)
for P: (0.1 IN 1 + 0.1 IN 2 + 0.5 IN 3) - (OUTs 1 to 3)
for K: (IN 1 + IN 2 + 0.5 IN 3) - (OUTs 1 to 3).

The thus estimated values were compared with total nutrient stocks in the soils of Kisii and southern Mali. The resulting values for N, P, and K indicated annual losses of the nutrient stocks in the order of magnitude of 1.2% for N and 0.35% for both P and K. These values, however, are very strongly affected by the assumptions made in the calculations of the INs and OUTS.

CONCLUSIONS

The nutrient balance results obtained for the subcontinental study paint a rather gloomy picture. Soil fertility is really at stake; however, it is risky to draw conclusions from low-resolution, aggregated studies. Generally, the largest unit for which soil nutrient balances can be quantified is the field, whereas larger spatial scales can only be dealt with through generalization and aggregations (Stoorvogel & Smaling, 1997). For nutrient balances, aggregation is a very delicate issue, as the balance itself is made up of at least 10 parameters (Table 2-1), which are in some cases outcomes of regression analysis on again more basic parameters. Also, a negative balance does not necessarily mean that crop production declines instantly because soils may have a large buffering stock of nutrients, sufficient to keep production going for many years (Smaling et al., 1996).

Based on this, we suggest that the subcontinental results should be treated as general awareness raisers, i.e., that soil fertility decline in Africa is a threat and needs attention, just like nutrient accumulation in some parts of Europe needs attention. At the national and subnational levels, results are meant to alert national and subnational policy makers and other stakeholders. Research and development efforts can be better targeted, but again the results do not reveal much on differences in farmers' management and strategies. This becomes visible only during farm-level monitoring activities, as carried out during the NUTMON pilot (Van den Bosch et al., 1998). Similar work is going on in several African countries, such as Kenya (Shepherd & Soule, 1998), Mali (Defoer et al., 1998), Ethiopia (Elias et al., 1998), and Tanzania (Baijukya & De Steenhuijsen Piters, 1998). In the recent past, different authors (e.g., Prudencio, 1993; Brouwer et al., 1993; Carter & Murwira, 1995; De Steenhuijsen Piters, 1995) have shown how risk-averse farmers in West and southern Africa cherish and exploit spatial variation in soil fertility. Analogies in the field of soil and water conservation also are plentiful (Tiffen et al., 1994; Rey et al., 1996), and clearly signal a warning to those who tend to rely only on averages and smoothness of trends. Survival strategies of African farmers are apparently underestimated (Scoones & Toulmin, 1998).

When considering the suitability of the nutrient balance as a land-quality indicator for nutrients, no index can be put forward as most obvious. Among the possible indices, the ratio of nutrient balance to nutrient stocks may be considered as the best one, but it is not easy to determine. The rather easy to determine ratio (IN 1 + IN 2)/(total inputs) and the more difficult (OUT 1 + OUT 2)/(total outputs) have been worked out to some extent in this chapter but do not seem too promising. The observed difficulties make it worthwhile to look further for other approaches. Theoretically there are opportunities in chemical soil analysis. The number of required data, the variability that is to be expected, and the high costs make such alternatives not very attractive.

Can we still say that soil fertility is at stake in Africa? Yes, because apart from the results of the studies presented above, there are a number of on-station and on-farm medium- and long-term trials that quantitatively support that statement. Figure 2-2 shows declining soil fertility in a long-term trial in central Kenya, and Table 2-7 summarizes changes in soil nutrients observed during the

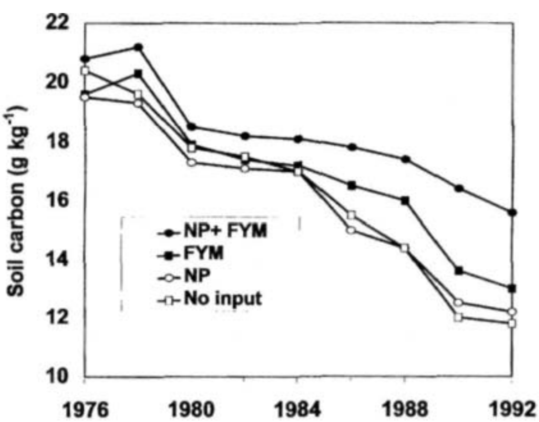

Fig. 2-2. Effect of applications of farmyard manure (FYM, 10 t ha^{-1} yr^{-1}), mineral fertilizer (N-P, 120 kg N ha^{-1} yr^{-1} and 52 kg P ha^{-1} yr^{-1}), and FYM (10 t ha^{-1} yr^{-1}) + N-P fertilizer (120 kg N ha^{-1} yr^{-1} and 52 kg P ha^{-1} yr^{-1}) on soil organic C at 0 t-o 25-cm depth at Kabete, Kenya (S.M. Nandwa, 1997, unpublished data).

Table 2-7. Changes in soil properties in the top 20-cm layer in nonfertilized, continuously cropped Kenyan soils, †

	Organic C		Mehlich P		Exchangeable K		pH in H_2O	
Site	T1	T2	T1	T2	T1	T2	T1	T2
	— g kg^{-1} —		— mg kg^{-1} —		mmol$_c$ kg^{-1}			
Alfisol (clayey)‡	30.7	29.9	25.8	25.2	7.2	8.1	5.1	4.9
Alfisol (sandy)§	6.8	4.8	30.6	24.7	2.7	3.5	7.0	6.9
Oxisol¶	20.5	20.1	17.2	13.4	2.0	1.7	5.1	4.7
Psamment#	7.9	6.7	27.0	25.1	4.9	2.9	7.7	7.0
Ultisol (clayey)‡	26.2	24.9	27.7	24.5	18.7	13.0	5.8	5.8
Ultisol (clayey)‡	15.7	15.8	14.8	13.2	4.6	4.0	5.4	5.3
Ultisol (loamy)¶	13.0	12.1	12.9	14.7	6.8	5.1	5.6	5.3
Ultisol (sandy)††	4.9	3.9	5.8	5.5	1.6	1.4	6.3	5.8

† Source, Smaling and Braun (1996).
‡ T1 = 1988, T2 = 1991.
§ T1 = 1988, T2 = 1990.
¶ T1 = 1988, T2 = 1992.
# T1 = 1987, T2 = 1990.
†† T1 = 1987, T2 = 1991.

Fertilizer Use Recommendation Project in different parts of Kenya (Smaling & Braun, 1996). But is soil fertility at stake all over Africa? No, certainly not! The average nutrient balance may be negative, but thousands of farms will be able to show sustainable nutrient management strategies at satisfactory production levels. And if researchers, farmers, and other stakeholders in the agricultural sector are ready to learn, listen, and subsequently teach, we may be on our way to a better future for agriculture in Africa.

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3 Soil Fertility Management in Africa: A Review of Selected Research Trials

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ABSTRACT

The increasing recognition of soil fertility depletion as the main biophysical factor limiting crop production in many African smallholder farms has raised interest in using data from past fertilizer studies to identify options for increasing agricultural production. This review of selected fertility research trials in sub-Saharan Africa reveals a pool of information (i) on the principles of fertilizer application for efficient nutrient use and (ii) on potential problems arising with continuous use of fertilizers in intensively cultivated systems. Adequate soil fertility for sustained crop yields can be obtained with combined use of mineral fertilizers and organic materials. Continuous use of N fertilizers can acidify soil, which then requires liming when organic inputs are limiting. Increased deficiencies of N, P, and other nutrients can be expected as a result of intensive cultivation and unbalanced fertilizer use. The use of mineral fertilizers by many smallholder farmers remains low because of socioeconomic constraints. This suggests that locally available organic materials will continue to be used as sources of nutrients. Future soil fertility trials should, therefore, particularly aim at identifying practices for judicious use of organic materials and their combination with mineral fertilizers. Shortcomings of past soil fertility research include limited economic analysis of results and use of trial sites and management that poorly represented those of smallholder farmers. Future research should strive for active participation of fanners, longer time frames to fully evaluate residual effects and rigorous economic analysis of results.

Sub-Saharan Africa (hereafter referred to as Africa) is characterized by diverse agricultural systems that are typically low input and based on subsistence farming. Traditional shifting cultivation and rotational systems permitted low but relatively stable food production on relatively poor soils. Rotational fallows are ecologically sound in low capital input areas (Sanchez, 1976). As population and pressures for land use increase, fallow intervals decrease in length until permanent intensive cultivation predominates. With time, these farms become subdivided and more intensively cultivated. Shifting cultivation continues to be practiced in only isolated locations and often at the expense of dwindling forest reserves and other natural habitats (Tukahirwa, 1992).

Substantial quantities of nutrients can be lost in permanent cultivation systems through offtake in harvested products and crop residues and through loss by runoff and leaching and as gases. Stoorvogel and Smaling (1990) and Stoorvogel et al. (1993) estimated high net nutrient losses totaling about 9.3 million tonnes in 1983 in Africa. Nutrient depletion can be particularly high in countries with high population densities, such as Ethiopia, Kenya, Malawi, and Rwanda (Smaling et al., 1997, this publication). Even more alarming is the projected figure for nutrient losses of up to 13.2 million tonnes in Africa by the Year 2000.

Nutrient depletion is complicated by the low inherent fertility of many soils, of which >80% have chemical or physical limitations to crop production (Sanchez, 1976). Nutrient depletion has been suggested as the main biophysical factor contributing to decreasing agriculture production in Africa since the mid-1960s (Vlek, 1993; Van Reuler & Prins, 1993; Sanchez et al., 1997b, this publication). Replenishment of soil fertility has therefore been singled out as one main activity likely to result in positive benefits associated with enhanced crop production, increased coverage of the soil surface with vegetation, and increased soil biological activity (Sanchez et al., 1997a).

Soil fertility replenishment can be achieved through the use of fertilizers, both organic and mineral. Where fertility depletion is already high, relatively small amounts of crop residues and animal manures are produced, and mineral fertilizers become the principal sources for building up nutrients in soils. But before fertilizer use is adopted, farmers must be aware of the fertilizer forms, methods of use, and potential benefits accruing from their use. In this chapter, we review selected soil fertility trials in Africa in terms of their contribution to the pool of information on increased and sustainable yields from efficient fertilizer use.

FERTILITY RESEARCH IN SEMIARID AFRICA

The semiarid zone has been defined by Deckers (1993) as an area with a growing period ranging from 75 to 179 d. Entisols, Alfisols, and Vertisols are the main soils of the area. Entisols are mainly composed of quartz and have low water-holding capacity and nutrient content. Entisols are weakly structured and prone to water and wind erosion. Leaching can hamper efficient use of fertilizers on Entisols. Alfisols have a clay accumulation horizon and a low capacity to store plant nutrients. Vertisols are characterized by a high content of swelling clay with usually high fertility, except that P availability is generally low and high N losses can occur under waterlogging conditions.

Soils in the semiarid zone generally have low organic C and total N contents because of low biomass production and a high rate of decomposition (Mokwunye et al., 1996). Nitrogen and P are limiting nutrients. Soil P stocks are low, but the low-activity clay of these soils has a relatively low capacity to fix added P (Bationo & Mokwunye, 1991). Therefore, the P requirement for maximum yield is often low (Mokwunye, 1979; Osiname, 1979).

Characteristics of the soils in the semiarid zones present problems of efficient use of applied N. Studies with ^{15}N in the semiarid tropics (Ganry et al., 1978; Gigou & Dubernard, 1979; Chabalier & Pichot, 1979) indicate increased loss of N from applied fertilizer with increasing rates of fertilizer application and high N losses regardless of N sources. Mughogho et al. (1986), in a summary of ^{15}N research by the International Fertilizer Development Center (IFDC) in semiarid areas of West Africa, reported that calcium ammonium nitrate (CAN) significantly outperformed urea in plant N uptake, which was translated into significantly higher yields of pearl millet *[Pennisetum glaucum* (L.) R. Br.]. Total plant uptake of fertilizer N, however, was low (20 to 37%), and losses were severe (25 to 53%). The majority of N remaining in the soil was found in the 0- to 15-cm layer. Ammonia volatilization was believed to be a cause for the N loss.

Field studies to compare N sources and methods of placement (Christianson & Vlek, 1991) showed that millet uptake of ^{15}N was almost three times higher from point-placed CAN than point-placed urea. Fertilizer N uptake by the plant was reduced by 57% when CAN was broadcast rather than point placed. Although urea acidifies the soil faster than CAN, its higher analysis appears to outweigh any deleterious effect induced in soil by its use. The high soil-acidifying effect of ammonium sulfate has made it less popular.

Split application of N fertilizer can considerably improve the efficiency of the applied N (Uyovbisere & Lombin, 1991). In a ^{15}N experiment conducted in southern Niger with sorghum *[Sorghum bicolor* (L.) Moench], 8% of the applied N for the first split and 19% for the second split were recovered in the grain (ICRISAT, 1989). Large positive and additive effects of crop residue and fertilizer application have been reported in the Sahelian zone (Fig. 3-1), where soil organic matter (SOM) content is low. Grain yields in the control plots were low and steadily declined during this 4-yr study. The results indicate that continuous cereal grain production on these soils will be more successful when mineral and organic fertilizers are combined (Janssen, 1993; Palm et al., 1997, this publication). In the Sudanian zone, long-term studies indicate that sustainable sorghum production can be obtained only when mineral fertilizers are combined with manure (Fig. 3-2). The combination of organic materials with mineral fertilizers also improves SOM and pH (Bationo et al., 1995).

Although yield responses to fertilizer and organic inputs are generally positive in experiments in the semiarid zone, the responses can vary with the amount of rainfall (Pieri, 1973; IRAT, 1974). Split applications of N fertilizer can be adjusted during the season according to the degree of water stress (Piha, 1993), and conservation of water can enhance the beneficial effects of fertilizer application (Mokwunye et al., 1996). In farmer-managed trials in Burkina Faso, sorghum

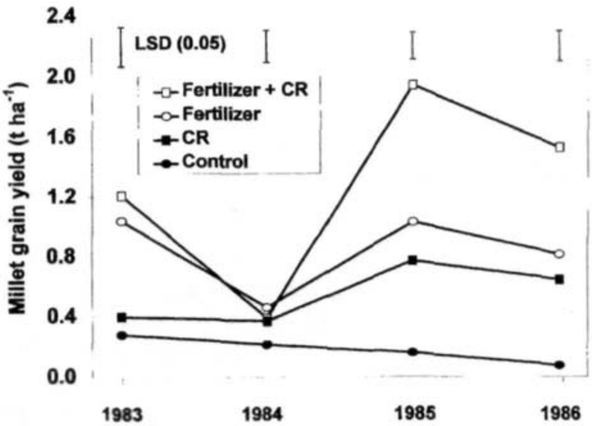

Fig. 3–1. Effect of mineral fertilizer and crop residue (CR) on pearl millet grain yield in Niger (adapted from Bationo et al., 1993).

grain yields were higher with the combination of fertilizer and tied ridges than with either fertilizer or tied ridges alone (Nagy et al., 1990). In Zimbabwe, sorghum yields were increased from 118 to 388 kg ha^{-1} using 1.5 m tied ridges, and to 1071 kg ha^{-1} when 50 kg N ha^{-1} was applied to the tied ridges during a low rainfall season (Nyakatawa, 1996). Thus, for the 34% of Africa that is semi-arid and characterized by unreliable and low rainfall, the relationship between soil water balance and crop yields plays a major role in the use of fertilizers.

Cropping systems have been observed to influence N use efficiency. Bationo et al. (1997, unpublished data) found that mean grain yields for 4 yr were lower for continuous cropping of pearl millet at N rates from 0 to 45 kg N ha^{-1} than for millet-cowpea *[Vigna unguiculata* (L.) Walp. sp. *unguiculata]* and millet-groundnut *(Arachis hypogea* L.) rotations. Higher responses with rotations than with cereal monoculture have similarly been obtained for a maize *(Zea mays* L.)-cowpea rotation in Zimbabwe (Mukurumbira, 1985). In Malawi, MacColl (1989) showed that grain yield of the first crop of maize following pigeonpea

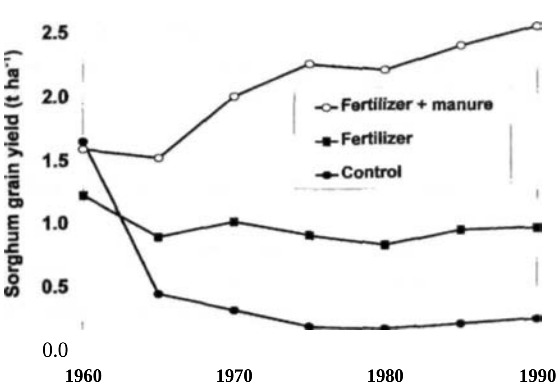

Fig. 3-2. Sorghum grain yield as affected by mineral fertilizers and manure in the Sudanian zone of West Africa (adapted from Sedogo, 1993).

[*Cajanus cajan* (L.) Millsp.] averaged 2.8 t ha^{-1} higher than that following continuous maize with 35 kg N ha^{-1} each year.

Considerable P research in the semiarid zone of West Africa has focused on the suitability of direct application of PR as an alternative to soluble P fertilizers (Gerner & Mokwunye, 1995). Direct application of ground, reactive PR (i) redresses P deficiency, (ii) has a strong residual effect, and (iii) does not acidify the soil. The agronomic effectiveness of PRs depends on their chemical and mineralogical composition and soil and plant factors. West African PRs tested in field trials include Tahoua and Pare W from Niger, Tilemsi from Mali, Kodjari from Burkina Faso, and Hahotoe from Togo (Sedogo et al., 1991; Bationo et al., 1992, 1997). The results indicate that Tilemsi PR and Tahoua PR could be viable alternatives to soluble imported fertilizers. Research by IFDC and collaborating national institutions has shown that partial acidulation of low-reactivity PRs, such as Pare W PR, results in improved performance (Bationo et al., 1986; 1992; Buresh et al., 1997, this publication).

Low soil fertility and low use of organic and mineral fertilizers are the greatest biophysical constraints to increasing agricultural productivity in farming systems in the semiarid region of Africa. The form, method, and timing of applications of the limited nutrient sources are important for efficient nutrient use for given water regimes and farming systems. Soil fertility in intensified farming in the semiarid zone can be maintained only through (i) the efficient recycling of organic materials, such as crop residue and manure, in combination with mineral fertilizers and (ii) the use of rotations with legumes (Giller et al., 1997, this publication).

FERTILITY RESEARCH IN SUBHUMID AND HUMID AFRICA

Deckers (1993) has defined the subhumid and humid zones as regions with a growing period of 180 to 269 d and >270 d, respectively. The predominant soils of these zones are Alfisols, Ultisols, and Oxisols. Alfisols are common in the subhumid tropics. They are frequently deficient in N and P, and they tend to acidify under continuous cultivation. Ultisols and Oxisols are well drained, contain little or no weatherable minerals, and have a clay fraction containing kaolinite and oxides and hydroxides of Fe and Al. These soils typically have low cation-exchange capacity and low inherent fertility. They frequently require balanced fertilization with several nutrients. Phosphorus sorption is associated with hydrous oxides of Fe and Al (Juo, 1981; Le Mare, 1981), and fertilizer P requirements tend to follow the order Oxisols > Ultisols > Alfisols (Warren, 1992).

Phosphorus

Numerous field experiments have demonstrated crop responses to small or moderate amounts of P fertilizers and residual benefits of P fertilizers to crops in seasons following the P application (Le Mare, 1959, 1974; Boswinkle, 1961). Jama et al. (1997) found that broadcast application of 10 kg P ha^{-1} as triple superphosphate (TSP) to maize on acid soils in western Kenya (Kandiudalfic

Eutrudoxs and Kandiudalfs, depending on the topsoil clay content) had a significant residual benefit to maize in the season following P application. Phosphorus fertilization at the tested 10 and 30 kg P ha^{-1} rates was financially attractive for maize.

Early literature highlighted the importance of mineralization of SOM as a source of plant-available P. Foster (1976) established that responses of cotton *(Gossypium hirsutum* L.), groundnut, and finger millet *[Eleusine coracana* (L.) Gaertn.] to P fertilizers on ferralitic soils in Uganda were inversely correlated to the level of SOM. A strong direct relationship between total soil organic P (P_0) and plant-available P was observed in Kenya (Friend & Birch, 1960) and southern Nigeria (Adepetu & Corey, 1976). The ability of SOM to supply P, however, has presumably decreased with the decline in total SOM as traditional cropping systems containing fallows were replaced by continuous cropping with little or no inputs of nutrients. Maroko et al. (ICRAF, 1997, personal communication) observed severe P deficiency on a Kandiudalfic Eutrudox continuously cropped with maize in western Kenya, even though the soil contained 0.30 g P_0 kg-^{1} soil (68% of the total soil P). Rotation of maize with a sesbania *[Sesbania sesban* (L.) Merr.] fallow significantly increased P in microbial biomass and light-fraction SOM and slightly reduced P deficiency for subsequent maize crops (Buresh & Tian, 1997; Buresh et al., 1997, this publication). The sesbania fallow, however, did not eliminate P deficiency, and P fertilization of maize was necessary for the sesbania-maize rotation to be financially attractive (ICRAF, 1997).

Early research examined the management of P to minimize contact between fertilizer P and soil, such as through banding, in P-fixing soils. Fox and Kang (1978) showed that banding of P fertilizer for maize was beneficial only at suboptimal rates (8 or 16 kg P ha^{-1}) on a sandy Alfisol in Nigeria. At P rates to obtain the maximum yield of 3.75 t ha^{-1} of maize grain, it was better to incorporate the fertilizer in the full volume of the soil. Banding may be satisfactory in soils with moderate P-sorption capacity, but in high P-fixing soils the band can limit root development and subject the crop to other nutrient stresses or water stress (Sanchez, 1976). An initial broadcast application of P can be required on soils with high P-sorption capacity and low available P (Yost et al., 1979).

With perennials, the uptake of P from within the soil profile and hence the optimal placement of P fertilizer can vary between dry and wet seasons. For banana *(Musa* sp.) in Uganda, Ssali (1972) observed that uniform surface (0 to 15 cm) placement of P fertilizers was effective in the wet season. In the dry season, root activity in the topsoil was much lower suggesting that deeper fertilizer placement or irrigation after fertilization was required in the dry season. Research with coffee *(Coffea arabica* L.) in Kenya revealed that root activity and uptake of P was highest near the soil surface in the wet season, but in the dry season when the topsoil dried out, the root activity was highest at 45 to 75 cm depth (IAEA, 1975).

A correction and maintenance fertilization approach with a one-time high rate of P fertilizer to reestablish optimum soil fertility levels for high productivity followed by periodic maintenance applications of P fertilizer has been proposed (Pieri, 1987; Sanchez et al., 1997b, this publication). This approach may be particularly attractive with medium- or high-reactive PRs applied to acid soils near the PR source. The added PR would provide a gradual release of plant-available P and residual benefit for several years (Rajan et al., 1996; Sanchez et al., 1997b, this publication).

Nitrogen

When SOM in the topsoil is above 30 g kg^{-1} soil, as is the case on opening some subhumid and humid lands for cultivation, little or no response to N fertilizers may be obtained (Sobulo & Osiname, 1986; Mughogho et al., 1990). The supply of plant-available N from SOM diminishes within a few years because of the fast breakdown of SOM and the inability of the soil to retain the released N (Giller et al., 1997, this publication). Thus, many field experiments in the subhumid and humid zones have shown response of nonleguminous crops to N fertilizer (Jones et al., 1960; Scaife, 1968; Christianson & Vlek, 1991). Christianson and Vlek (1991), at a range of sites in West Africa, found (i) comparable maize yields with banded and point-placed N fertilizer, (ii) superiority of banding and point placement compared with broadcast application of N fertilizer, and (iii) comparable effectiveness of urea and CAN as N sources. Ssali (1990) similarly found statistically comparable yields of maize and common bean *[Phaseolus vulgaris* L.] following application of either CAN or urea on an Oxic Paleustult in Kenya. They concluded, however, that high-analysis urea (46% N) was financially more attractive than CAN (26% N) because of lower transport costs. Split application of N fertilizers to synchronize N supply with plant uptake of N is critical for high N use efficiency and minimal N loss (Arora & Juo, 1982; Mughogho et al., 1990).

Continuous use of N fertilizers, especially ammonium sulfate, induces soil acidity (Stephens, 1969; Wapakala, 1976; Aduayi, 1984; Juo et al., 1995). Stephens (1969) found at nine stations in southern and western Uganda that soil pH at 0 to 20 cm was reduced by about 0.3 units per 2.5 t fertilizer ha^{-1} after application of ammonium sulfate 4 yr. On a kaolinitic Alfisol at Nigeria, pH decreased from 5.8 to 4.5 during 5 yr of continuous maize cropping widi ammonium sulfate fertilizer (Juo et al., 1995).

One way of minimizing soil acidity from fertilizer N is by supplying N through biological N_2 fixation. Biological N_2 fixation from legumes can sustain tropical agriculture at moderate levels of output (Giller et al., 1994, 1997, this publication). Under favorable conditions, green manure crops can accumulate 100 to 200 kg N ha^{-1} in 100 to 150 d in the topics (Giller et al., 1994). Rhizobial inoculation in East and Central Africa can enhance yield of exotic food legumes with specialized rhizobial requirements {e.g., soybean *[Glycine max* (L.) Merr.] from China, pea *(Pisum sativum* L.) from Asia Minor, and common bean from Central America; Table 3-1}. Phosphorus fertilization can be necessary for effective growth and N_2 fixation by legumes (Ssali & Keya, 1986; Cassman et al., 1993).

Other Nutrients

Nutrients other than N and P have received relatively little attention, and reports on their deficiencies are limited (Le Mare, 1984; Kang & Osiname, 1985).

Table 3-1. Rhizobial inoculation response by legumes in East Africa.t

Test crop	Country	Site	Yield		Increase
			Uninoculated	Inoculated	
			t ha^{-1}		%
Soybean	Kenya	Homa Bay	2.52	3.57	42
	Kenya	Kabete	1.02	1.61	58
	Kenya	Mtwapa	2.33	3.85	65
	Rwanda	Kigembe	1.04	1.89	81
	Tanzania	Morogoro	**1.45**	2.21	52
Common bean	Kenya	Kabete	2.15	2.64	23
	Rwanda	Karama	0.80	1.00	24
	Tanzania	Morogoro	0.26	0.34	32
	Uganda	Makerere	1.59	1.61	9
Groundnut	Rwanda	Karama	0.44	0.56	29
Pea	Rwanda	Karama	1.13	1.38	23

+Source, Woomer et al. (1998).

Reasons for limited attention to nutrients other than N and P are that (i) traditional practices of fallowing are able to increase availability of nutrients in the topsoil (Jaiyebo & Moore, 1964; Stephens, 1967), (ii) the supply of these nutrients from soil is frequently sufficient for most crops for a number of years before response occurs (Foster, 1979), (iii) some N and P mineral fertilizers contain additional nutrients (e.g., sulfur in single superphosphate and ammonium sulfate), and (iv) organic inputs and crop residues contain nutrients in addition to N and P.

Anderson (1973) in a review on K responses of various crops in East Africa reported that responses to K fertilizers tended to increase with time following land opening or grass fallows. Singh and Goma (1995) likewise reported response of maize to K on an Oxisol in Zambia 3 yr after start of a long-term trial. Results with groundnut in Kenya showed some cases of greater response to K when it was applied with P, but the response was less striking in the subhumid and humid zones than in the semiarid zones (Tag et al., 1972). Research results indicate that increased intensity of cropping will lead to greater need for K inputs, especially for crops with high offtake of K in harvested products such as some root crops and bananas.

There are increasing reports that application of K or S in combination with N and P increases crop yields, suggesting an increased need for inputs of these nutrients as N and P deficiencies are alleviated (Vlek, 1990). The application of high-analysis fertilizers (e.g., urea and TSP) without S, can with continuous cropping, lead to S deficiencies (Friesen, 1991). Micronutrient analysis of common bean seed collected from Tanzania, Zambia, and Malawi suggested that Mo and Cu were the micronutients most likely to limit N_2 fixation and bean growth in eastern and southern Africa (Brodrick et al., 1995).

Liming can be essential for high crop yields on soils with high Al saturation. In Uganda, Foster (1976) concluded that liming was important at pH < 5.25. Acid-tolerant crops, such as cassava {*Manihot esculenta* Crantz) and yam [*Dioscorea esculenta* (Lour.) Burkill], may grow well at lower pH values and require less lime. Results from a 6-yr study on an acid Typic Paleudult (pH in water = 4.6, sand = 67% at 0 to 15 cm) in Nigeria indicate that relatively low rates of lime can sustain yields in a maize-cowpea rotational cropping system (Friesen et al., 1982). About 90% of maximum maize yield was obtained at 35% Al saturation. The critical level for Al saturation for cowpea ranged from 25 to 55%, depending upon cowpea variety and rate of mineral fertilizer. Liming can enhance use of applied fertilizer (Yamoah et al., 1992) and substantially increase exchangeable Ca, pH, extractable P, and effective cation-exchange capacity (Pieri, 1987; Yamoah et al., 1992; Lungu et al., 1993).

LESSONS FROM LONG-TERM EXPERIMENTS

Table 3-2 summarizes information from select experiments with arable crops for at least 7-yr duration. The experiments were basically designed to determine the effects of mineral fertilizers and organic inputs on crop yields and soil fertility. The results allow an examination of some issues associated with sustainability of crop production.

At all sites, there were positive yield responses to one or more nutrients added as mineral fertilizers. The responses were consistent for the duration of the experiments. This highlights the effectiveness of mineral fertilizers in increasing yield in arable farming systems in Africa. This potential is recognized by large-scale farmers, who have been able to sustain relatively high yields of maize (Kenya, Zambia, and Zimbabwe), tobacco *(Nicotiana tabacum* L.; Malawi and Zimbabwe), and coffee *(Coffea arabica* L.; Kenya) for periods of up to 30 yr.

In 9 out of 13 sites shown in Table 3-2, yields for mineral fertilizer treatments declined during the experiments. A decline in crop yields with application of only mineral fertilizer is further illustrated with results for maize during 19 years in Kenya (Fig. 3-3). Maize yields for application of mineral fertilizer started to become less than for farmyard manure (FYM) and mineral fertilizer plus FYM plus crop residues (CR) after 10 yr. Such declines might result from (i) soil acidification by the fertilizers, (ii) mining of nutrients as higher grain and straw yields remove more nutrients than were added (Scaife, 1971), (iii) increased loss of nutrients through leaching as a result of the downward flux of nitrate when fertilizer N is added, and (iv) decline of SOM. The depletion of nutrients, not added with fertilizers, to deficiency levels in the soil is a plausible explanation for declining yields in many cases. Many studies have shown that after replenishing nutrients initially limiting crop production, other nutrients quite often start to become limiting (Kenya Agricultural Research Institute, 1994; Singh & Goma, 1995).

Pieri (1995) reported that use of N fertilizer with sorghum monocropping in Burkina Faso accelerated the annual rate of SOM loss from 1.5% without fertilizer, to 1.9% with moderate rates of N fertilizer, and 2.6% with high N rates. In Kenya (Fig. 3-3), however, the application of NP fertilizer did not increase the decline in soil organic C. The decline in soil C over 16 yr was comparable for no fertilization (20.4-11.8 g C kg^{-1} soil), application of NP mineral fertilizer (19.5-12.2 g C kg^{-1} soil), and application of only FYM (19.6-13.0 g C kg^{-1} soil); see Fig. 2-2, Smaling et al., 1997, this publication). Soil organic C after 16 yr was

Table 3-2. Impact of soil management treatments on crop yield trends in selected long-term experiments from sub-Saharan Africa.

Number	Site	Soil description	Experiment duration	Test crops	Treatment! Mineral fertilizers (A)	Animal manures (B)	Crop residues (C)	A + Bor A + C	Liming or A + Liming
‡	Cdte D'lvoire								
	Bouake	Ferralitic§	1969 to 1990	Cotton	++S		+ S	++S	
	Korhogo	Ferralitic	1969 to 1990	Cotton	+ D				+ S
2	Senegal								
	Darou	Ferruginous	1957 to **1974**	Groundnut	+ D				
	Bambey	Ferruginous	1957 **to 1974**	Groundnut	+ D	+ S	+ D		+ D
3	Burkina Faso								
	Niangoloko	Ferruginous	1962 to 1984	Groundnut, millet		+ S			
	Saria	Ferruginous	1960 to 1983	Groundnut, millet	+ D	+ D	+ DD	+ S	+ S
4	Chad								
	Bebeda				+ S				
5	Tanzania	Ferralsol	1981 to 1988	Maize	+ D				
		Luvisol	1981 to 1988	Maize	+ D				
6	Zambia								
	Misamfu	Oxisol	1966 to 1981	Maize, groundnut	+ DD				+ S
	Magoye	Luvisol	**1966 to 1981**	Maize, groundnut	+ S				
	Katito	Ultisol	**1966 to 1981**	Maize, groundnut					+ S
7	Uganda								
	Serere	Ferralsol	1937 to 1964	Cotton, millet, sorghum, groundnut	+ D			+ S	
8	Nigeria								
	Samaru	Ferruginous	1964 to 1975	Cotton, millet, sorghum, groundnut	+ S				
9	Kenya								
	Kabete	Nitisol	1976 to 1996	Maize, bean	+ D	+ S	+ D	++S	

† + , yield higher than control; ++, yield relatively higher than + within the row; S, stable yield trend; D, measurable yield decline; DD, sharp yield decline.

‡ Sources: 1, Traore & Harris (1995); 2, 3, 4, Pieri (1995); Laryea et al. (1995); 5, 6, Singh & Goma (1995); 7, Research Reports, Serere Experiment Station; J.B. Byalebeka (1996, personal communication); McWalter and Wimble, (1976); 8, Singh and Balasubramanian (1979); 9 = Swift et al. (1994) and S. Nandwa (1996, personal communication).

Approximate USDA Soil Taxonomy equivalents: Ferralitic, Oxisol; Ferruginous, Alfisol; and Luvisol, Alfisol.

slightly higher (15.6 g C kg^{-1} soil) with combined application of NP mineral fertilizer and FYM.

The application of organic inputs as either animal manures or crop residues increased yields, but in many cases yield tended to decline with application of only organic inputs (Table 3-2). Crop residues were generally less effective than animal manures as a source of nutrients. Application of residues with high C-to-N ratio to soils can lead to short-term N deficiencies as a result of N immobilization.

Residues, however, can be more effective than manures with perennial crops. Sanders (1953) reported a 22% yield increase of coffee from manure and a 50% yield increase from banana trash mulches for a 10-yr period. Reports by Gilbert (1945), Bull (1963), and Robinson and Hosegood (1965) suggest that these responses were a direct result of improved soil nutrients, soil-water conservation, and modulated soil temperatures. Banana trash used as mulch contributed more to soil-water conservation and modulated soil temperatures than to supply of nutrients.

The combined use of mineral fertilizers and organic inputs increased yields and maintained stable yields for the duration of the experiments (Table 3-2). In almost all cases, the results of mineral fertilizer plus organic materials were additive effects of the two inputs. The application of FYM and CR with mineral N and P fertilizers resulted in greatest yields at Kabete, Kenya (Fig. 3-3).

The application of lime with or without mineral fertilizers tended to increase and sustain yield in many cases (Table 3-2). The comparable effects on yield for lime and for organic inputs with mineral fertilizers suggests that organic inputs may have a beneficial effect in reducing soil acidification. Wong et al. (1995) showed that application of FYM and calliandra {*Calliandra calothyrsus* Meissner) primings significantly lowered Al saturation from 80 to 68% on acid Oxisols of Burundi. The reduction in exchangeable Al, which was attributed

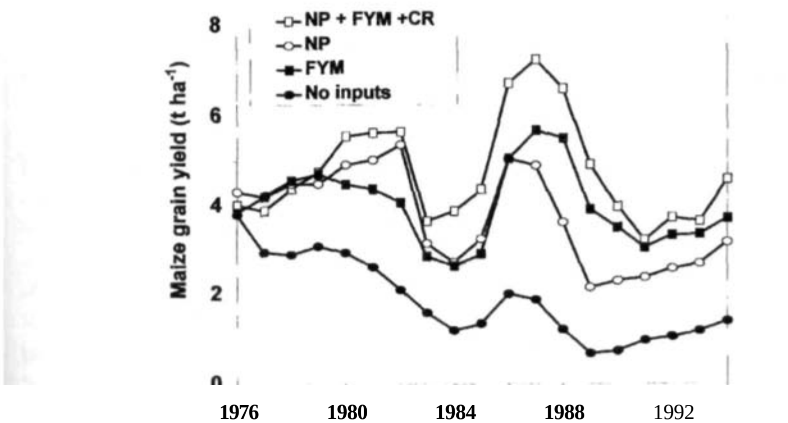

Fig. 3-3. Effect of applications of mineral fertilizer (120 kg N ha^{-1} yr^{-1}, 52 kg P ha^{-1} yr^{-1}), farmyard manure (FYM, 10 t ha^{-1} yr^{-1}) and returned crop residues (CR) on maize grain yields at Kabete, Kenya (S.M. Nandwa, KARI, 1997, unpublished data). Values are 3-yr moving averages.

mainly to the applied organic materials, increased maize grain yield. The beneficial effects of organic materials are reviewed in detail by Palm et al. (1997, this publication).

Results of the long-term experiments emphasize the need for greater use of fertilizers (mineral and organic) to remedy the nutrient deficiencies in Africa. For intensive and continuous crop production, these inputs should aim at balanced application of nutrients and avoidance of soil acidification.

IMPACT OF FERTILITY MANAGEMENT RESEARCH

Our review shows a history of quality research that supports fertilizer use in improved crop production. We have learned of the benefits of mineral fertilizer inputs combined with crop residues, manure, and biological N_2 fixation for conserving and maximizing nutrient-use efficiency. Yet, less fertilizer is being applied per unit land area in Africa than in other regions of the world (Woomer & Muchena, 1996; FAO, 1996).

We technically view the limited adoption of fertilizer use by farmers as a symptom of deficiencies in many research trials. The most significant appears to be their poor representation of farmers' conditions. Nearly all the research results reported in this review were obtained from experiments conducted on research stations or at field sites wholly managed by researchers. The studies have involved single crops or simple seasonal rotations of a few crops in contrast to the intercropping frequently preferred by smallholders. Under smallholder conditions, it is rarely possible to generate organic inputs to meet the rates reported in the research studies. There also is insufficient information on the optimum use of small amounts of mineral fertilizers to supplement nutrients contained in organic residues that may be imported on the farm.

Many important practical questions for smallholders thus remain unanswered because they were not built into the designs of these experiments. We propose mat in designing experiments to supplement data already generated in past research, scientists should trace their research activities to farm productivity. This requires involvement of farmers as active partners in all the events of the research programs.

Only a few studies had inferences to short-term economic optimum rates of mineral fertilizer application. Studies seldom consider appropriate fertilizer rates to sustain profitability on a long-term basis. Although the average fertilizer consumption rates in Africa are low, fertilizers are used on cash crops such as cotton, coffee, and oil palm that can steadily be marketed on a profitable basis (Vlek, 1990). If other crops could likewise be effectively marketed, the use of fertilizer would increase. This is supported by an example from Nigeria (Vlek, 1993) where farmers were willing and able to produce grain for the market and purchase the necessary fertilizer when they did not have to compete with subsidized grains. If research could demonstrate that using fertilizer on stable food crops was profitable, the adoption of skills and technologies for better fertilizer use would be an integral process of increased agricultural production.

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4 A Fertilizer-Based Green Revolution for Africa

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ABSTRACT

On average, <5 kg ha^{-1} of mineral fertilizer nutrients are applied to food crops in sub-Saharan Africa, the lowest rate in the world. Population pressures have caused traditional systems of shifting cultivation to break down. Soil nutrients are being depleted at an alarming rate, leading to environmental degradation and food insecurity. To reduce poverty and assure food security, African agriculture must grow at 4 to 5% per year, more than twice the rate of recent decades. This growth is unattainable without using significantly greater quantities of mineral fertilizers. Excellent agronomic response to fertilizers has been observed in >600 000 half-hectare, on-farm demonstration plots in the major food crops in 12 countries. In Ethiopia, with the increased use of mineral fertilizer, improved-seed, better extension advice, and favorable rainfall over most of the country; record harvests of the major food crops have been achieved over the 1995-1996 and 1996-1997 seasons. The country has become food self-sufficient and advanced closer to the goal of food security. Attention must be given to improving the efficiency of use and supply of fertilizers to make them more affordable to farmers. Equally important is the role of agricultural research and development in devising technologies and strategies that ensure the sustainability of food production to meet the demand of an ever-increasing population. Priority on the agenda should be given to developing nutrient management practices in which all nutrient sources are judiciously integrated and losses to the environment are minimized.

Between 1997 and 2020, population in sub-Saharan Africa (hereafter referred to as Africa) will more than double to over 1.1 billion people (Dyson, 1995; Rosegrant et al., 1995). Investments by national governments and the international community have been insufficient to arrest poverty, assure food security, and reduce environmental degradation in this continent. Indeed, if present trends continue, food insecurity, malnutrition, and resource degradation will increase, and by 2020, it is conceivable that Africa will need to import between 50 and 70 million tonnes per year of foodstuffs (mainly cereal grains) to meet the demands of

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the increased population (Dyson, 1995; GCA, 1996). Almost certainly, Africa will not have the economic resources to procure such huge volumes of food on a commercial basis nor will the international community be willing to provide it as concessional sales or food aid.

Since most of the poor in Africa are rural, and agriculture is their mainstay, it follows that agricultural development must be the central strategy for economic growth and poverty alleviation (Birdsall, 1995). It also is important to stress that hunger, poverty, and environmental degradation in Africa are intimately correlated, and that any action to reduce poverty and hunger will assist in minimizing environmental degradation as well (Cleaver & Schreiber, 1994).

The critical role of agriculture in Africa's development is not universally accepted by many governments. Consequently, in most countries, agriculture has been growing more slowly than population, which has resulted in decreasing incomes in real terms. The major cause of the poor performance of the agriculture sector is not a dearth of improved agricultural technology that can empower the small-scale farmer to increase productivity. Rather it is poor economic and agricultural policy; inadequate investment in infrastructure and rural education; insufficient agricultural services, such as research, extension, credit, input supply, and marketing; and low investments in rural health care (Cleaver & Donovan, 1995).

In most regions of the world, increases in food supply over the past two decades have resulted mainly from raising yields. The only major exceptions are Africa and the *Cerrado* of Brazil, where most of the growth in production has occurred because of expansion of the cultivated area (Borlaug & Dowswell 1994; Dyson, 1995). It is widely perceived that technology-based agriculture has largely bypassed Africa. Where land is plentiful, *slash and burn* shifting cultivation persists, and this is still common in much of Africa. However, where population pressures have reduced the fallow period, a sedentary low-yield agriculture has arisen. But no matter what the variations in the agricultural system, the common base is that plant nutrients are the minimum factor for crop production (Jansson, 1995). Traditional agriculture results in mining soils of plant nutrients by removing crop residues, leaching, and soil erosion (Smaling et al., 1997, this publication). According to Stoorvogel and Smaling (1990), about 200 million ha of cropland in Africa have lost 660 kg N ha^{-1}, 75 kg P ha^{-1}, and 450 kg K ha^{-1} during the last 30 yr, primarily by removing crop harvests (Bumb, 1995; Sanchez et al.,1997, this publication). These figures amount to a loss of plant nutrients in the range of about 8 million tonnes N-P-K annually.

Traditional fanning systems in Africa are responsible for the loss of 4 million hectares of forest that are cleared annually to give room or substitute for the cropland that has become unproductive because of nutrient depletion. This practice is leading to disastrous environmental consequences, such as soil erosion, weed invasions, impoverished postfire-climax vegetative ecosystems, and loss of biodiversity (Borlaug & Dowswell, 1995). The solution is clearly not to expand food production horizontally to keep pace with population growth at the cost of environmental degradation. Instead, the solution is to provide adequate soil nutrients by increasing the use of mineral fertilizer, combined with organic inputs that build up organic matter in the soil, and the complementary practices of using improved seeds and proper plant population, weed control, and other cultural practices.

Fertilizers have played and will continue to play an important role in increasing the food supply for future generations. It is estimated that around 50% of the annual global food harvest comes from the application of mineral N fertilizer alone (Dyson, 1995). The judicious use of mineral fertilizers can play a critical role in preventing resource degradation that results from nutrient mining, and from the exploitation of fragile lands or the clearing of habitat-rich forests. In Africa, fertilizer consumption on food crops is the lowest in the world—probably no >5 kg ha^{-1} of nutrients, when fertilizer use on cash crops is subtracted from aggregate statistics.

Increased fertilizer use in Africa can create a win-win situation, by promoting more efficient crop production and reducing soil degradation. Mineral fertilizers should be at the core of strategies to restore soil fertility and raise crop productivity, although their use should be a part of integrated systems of nutrient management in which organic fertilizer sources are included. Organic sources of nutrients, however, will be complementary to the use of mineral fertilizers, and not the other way around. Exclusive use of organic fertilizers will increase food production at best by 2% yr^{-1} (Hiyami & Ruttan, 1985), well below the population growth rate, and not even close to the 5 to 6% required to reduce poverty and assure food security. The World Bank's 1989 long-term perspective study (1990 to 2020) to permit gradually improved food security and increased rural incomes set agriculture growth in Africa at 4% a year (Cleaver & Schreiber, 1994). Because the overall performance of Africa for 1990 to 1996 did not attain the 4% target, many people including Cleaver (1996, personal communication) say that 5% per year agricultural growth is probably necessary to have a significant impact on poverty reduction. With population growth around 3% per year, this would be only a *2%* net increase in per capita production.

It also is important to mention that sources of organic manure are limited in most African countries. Even in Ethiopia, where livestock numbers are significant, manure is primarily used as a cooking fuel and rarely to improve the fertility of the soil. Moreover, use of other organic sources, such as green manures, presupposes growing the manure crop at the expense of a food or cash crop (Giller et al., 1997, this publication). Finally, alley cropping and agroforestry approaches to maintaining soil fertility are knowledge-intensive, nutrient management systems that have met with limited success, especially where poverty and hunger force farmers to employ desperate short-term survival strategies that take precedence over longer term sustainability practices. Hence, efforts should be made to increase the efficient use of mineral fertilizers through sound policies and education, to attain economic growth and food security targets while minimizing the damage to the resource base.

SASAKAWA-GLOBAL 2000 EXPERIENCE IN AFRICA

The term *Green Revolution* has been much misunderstood since it was first coined by William Daud, former administrator of USAID, some 30 yr ago. We define the Green Revolution as the beginning of a new era for agricultural research and development in the third world, one in which modern principles of genetics and plant breeding, agronomy, plant pathology, entomology, cereal technology, and economics have been applied to develop higher yielding technologies appropriate to the conditions of local farmers (Borlaug, 1988). The Green Revolution concept to produce more food by increasing the productivity of the more favorable agricultural lands becomes especially relevant as the per capita availability of arable land declines. It is to these principles that we adhere when referring to a Green Revolution for Africa.

Sasakawa-Global 2000 (SG 2000) began its agricultural projects in Africa in 1986. Our mission was to contribute towards the attainment of food security through the adoption of productivity-enhancing technologies by small-scale farmers. The SG 2000 projects have been funded since their inception by the Sasakawa Foundation, recently renamed as the Nippon Foundation, and they are enthusiastically supported by former U.S. President Jimmy Carter. Projects are currently in operation in Ghana, Benin, Togo, Nigeria, Guinea, Mali, and Burkina Faso in West Africa and Ethiopia, Eritrea, Tanzania, Mozambique, and Uganda in East and southern Africa. Similar projects also were operated previously in Sudan and Zambia.

At the outset, it is important to make clear that SG 2000 conducts the majority of its program activities with—and through—national research and extension organizations. We do not operate separate parallel programs, and SG 2000 only has six field directors to supervise operations in 12 countries. The core of the SG 2000 projects are dynamic field testing and demonstration programs for the major food crops in which improved technology exists but for various reasons was not being adequately extended to farmers (Borlaug & Dowswell, 1995). The SG 2000 projects work under the leadership of the national extension departments of the relevant ministries of agriculture. Practically all the technical extension staff from those departments are thoroughly involved in the planning, implementation, and monitoring of SG 2000 field programs. At the regional or state level, this leadership role is transferred to the regional or state offices of agriculture, who appoint district or zonal coordinators for the field program. The district offices of agriculture assign the frontline extension staff who assist the participating farmers in the establishment of their demonstration plots and help in other project-related field activities (such as field days and postharvest work).

The selection of participating farmers is done by the frontline extension staff in collaboration with their supervisors. The participation by farmers in the establishment of SG 2000-sponsored demonstrations is voluntary. Farmers discuss and agree on the conditions of participation, which usually involve agreement on the part of the farmers to follow application of the recommended kinds and amount of production inputs followed by proper cultural practices. Special efforts are made to engage women farmers, particularly in countries where food production undertakings are the responsibility of women.

SG 2000 works mainly in agroecologies known for their high agriculture potential, and its field program emphasizes the application of research-led information that can bring about dramatic increase in productivity. Working with national extension services during the past 11 yr, small-scale farmers have grown

>600 000 demonstration plots (0.25-0.5 ha). Most of these plots (known by different acronyms depending on the country) have been concerned with demonstrating improved technologies in maize *(Zea mays* L.), wheat *{Triticum aestivum* L.; T. *turgidum* L. *var. durum),* sorghum *[Sorghum bicolor* (L.) Moench], cassava *(Manihot esculenta* Crantz), grain legumes, barley *(Hordeum vulgare* L.), potato *(Solanum tuberosum* L.), and, in the case of Ethiopia, tef *(Eragrostis tef* Zucc). Approximately two-thirds of these plots have been planted to maize, either as a monocrop, or in various intercropping patterns with cassava or grain legumes, or in several multiple cropping patterns with velvet bean *(Mucuna pruriens* var. *utilis)* and other green manure crops.

The improved technological packages taken to farmers by frontline extension staff, with support from SG 2000, are derived from national and international research systems and are upgraded as new research information or cultivars become available. The packages of improved crop management practices being recommended include (i) the use of the best available commercial cultivars or hybrids, (ii) improved agronomic practices that assure proper rates, dates and methods of planting, timely weed control, efficient use of available soil water, and when needed, crop protection chemicals, (iii) proper application at moderate levels of appropriate fertilizers to restore plant nutrients in the soil, and (iv) improvement of on-farm storage structures and methods for harvested grain, both to reduce postharvest losses and to extend the marketing season by safely holding stocks until prices are more favorable.

One distinctive feature of the SG 2000 technology-transfer approach is the size of the demonstration plot, which is usually between 0.25 and 0.5 ha, and constitutes the actual site on which improved farming practices are appraised by the farming community. To add to the economic realism, participating farmers are asked to pay the commercial cost of inputs used to conduct the demonstrations on their land. While there are differences among SG 2000 project countries, the trend is for farmers to pay 50 to 100% of the cost of inputs prior to planting, to help ensure that they become stakeholders from the beginning, with a sense of ownership and obligation for repayment, instead of fostering dependence on external aid. After one or two seasons, a participating farmer is *graduated* and extension workers move on to new farmers who are enrolled in the demonstration program.

The larger size demonstration plot recommended by SG 2000 not only allows farmers to make a more realistic appraisal of the recommended technology but also affords them with a clear measure of the economic returns on their labor and capital. In contrast, in the pervasive World Bank-supported *Training and Visit* extension system the demonstration plot is between 0.005 and 0.01 ha. With the larger test plots, farmers measure increased yields in terms of 100 kg, not kilograms. The SG 2000 demonstration plot approach has gained wide recognition and approval by extensionists as a very effective tool in the diffusion of improved technologies to farmers.

Simultaneously with the dynamic field demonstration program, SG 2000 project staff strive to get the attention of policy makers, since we believe that international assistance should be used only as a catalyst, not as a substitute for national action. The SG 2000 philosophy is that once the technology has been

Table 4-1. Average maize yield in demonstration and farmers' plots in SG 2000 countries.!

	Maize yield										
	Demonstration plots									Farmers	Average increase over
Country	1987	1988	1989	1990	1991	1992	1993	1994	1995	plots	farmers'plots
	t ha-[1]										%
Ghana	2.8	4.0	3.3	3.2	4.2	2.8	3.3	3.0		1.3	**150**
Tanzania			5.2	5.2	4.9	3.9	2.4	4.8		1.4	208
Benin			2.8	2.4	2.9	3.4	3.2			1.0	**187**
Togo				2.5	3.5	3.8	3.3			1.2	**187**
Ethiopia							5.2	5.5	5.7	1.7	220

t Source, Sasakawa-Global 2000 files.

convincingly demonstrated to African fanners and governmental leaders, they should pick up the lessons. In other words, Africans should make the decisions as to their development strategies, although the donor community can and should assist African countries in developing national capacity.

The SG 2000-supported demonstration plots are strategically located and are reinforced by well-managed field days and information campaigns to generate wider scale awareness and interest, not only among neighboring farmers but also among key officials at different levels of government. It is not surprising to have ministers and even heads of state attending field days and engaging in constructive dialog with farmers. Parallel to the field demonstrations, SG 2000 staff work closely with national government leaders in agriculture-sector planning and policy formulation to enable farmers to continue using the improved technology.

In virtually all of the SG 2000 project countries during the past 11 yr, demonstration plot yields have been two to three times higher than those obtained in the control plots or in traditional farmers' fields. Table 4—1 shows the yield performance in maize obtained by participating farmers in selected SG 2000 countries. Thousands of field days have been organized and attended by hundreds of thousands of farmers who are eager to learn about the success of their fellow farmers. A great deal of *copying* from farmer to farmer also is commonly observed. This demonstrates that the technology is not only easily understood and implemented but also profitable. Another feature we have observed is that when a farmer innovates in one crop and understands the production principles, similar innovations in other crops will soon follow.

If we were to single out one country that vividly demonstrates the potential for a Green Revolution in Africa, Ethiopia would be the example for others to follow. Like most countries in Africa, Ethiopia is predominantly rural and heavily dependent on agriculture. Agricultural production accounts for 55% of the gross domestic product, and 80% of the population make their livelihood from agriculture. This sector is dominated almost entirely by small-scale, resource-poor farmers who produce 90 to 95% of all cereal grains, pulses, and oilseeds, and 98% of the coffee {*Coffea arabica* L.; Central Statistical Authority, 1996b). Cereals account for nearly 84% of the total cultivated area and nearly 70% of the caloric intake of the Ethiopian population (Central Statistical Authority, 1996a). The most important cereal grain crops are tef, maize, sorghum, barley, and wheat in that order.

Table 4-2. Fertilizer imports in Ethiopia.

Year	DAP	Urea	N	P	Total NP	Growth over previous year
	1000 tonnes					%
1993	97	22	27	20	47	
1994	181	28	45	37	82	74
1995	202	44	56	41	97	18
1996	280	65	80	57	137	41

Source, National Fertilizer Import Authority 1996, Addis Ababa.

As in other African countries, Ethiopian agriculture stagnated during the 1970s and 1980s, and the country was facing chronic difficulties to feed its ever-increasing population, which presently is estimated at around 55 million people. Annual food imports were close to 1 million tonnes during the last 10 yr, mostly as food aid (mainly wheat). This bleak food-aid dependency has experienced a remarkable reversal during the past 2 yr, partially because of the support provided by the Government of Ethiopia led by Prime Minister Meles Zenawi to put agriculture at the forefront of economic development.

The Ethiopian experience has resulted from a combination of a political leader's vision and a fortuitous encounter with the field activities of SG 2000, operating in Ethiopia since 1993. During a visit of former U.S. President Jimmy Carter in September 1994, an invitation was made to Prime Minister Meles (then President of the Transitional Government) to accompany Mr. Carter on a field inspection tour of some project sites. Mr. Meles was clearly impressed by the demonstration plots grown by the farmers, in which improved seed and mineral fertilizers were used in combination with other improved husbandry practices. The plots promised to yield three to four times the average yields obtained in the area. That watershed visit was the beginning of what is now known in Ethiopia as the Intensified Extension Campaign, which is fully backed and supported by the government at all levels. This campaign entails the establishment of 0.5-ha demonstration plots on farmers' fields in all food crops for which technology is available from the national research system and implemented on a massive scale covering all agricultural districts of the country. Hundreds of field days are carefully organized to spread the message among the farming community about the benefits of adopting improved technology.

As the result of this campaign, fertilizer imports into the country have increased from 47 000 tonnes N and P in 1993 to 137 000 tonnes N and P in 1996 (Table 4-2). Farmers have been using diammonium phosphate (DAP) fertilizer almost entirely for >20 yr, while urea as a source of N is only a recent introduction and still needs to be popularized. Consumption of mainly DAP creates an imbalance of the N-to-P nutrient ratio. Although most agricultural soils in Ethiopia are deficient in both N and P, and present fertilizer research recommendations across the country range from 70 to 100 kg N ha^{-1} and 20 to 30 kg P ha^{-1}, depending on soil type and specific crop, farmers still depend almost exclusively on DAP application. This then leads to an imbalance of insufficient application of N per unit of P (Table 4-2).

Table 4-3. Estimates of 1994-1995 and 1995-1996 area and production for major crops of private peasant holdings in Ethiopia, by region.

	Total area			Total production		
Region	1994-1995	1995-1996	Change	1994-1995	1995-1996	Change
	——1000 ha——		%	— 1000 tonnes——		%
Tigray	506	481	-5	304	527	74
Afar	17	24	47	15	19	32
Amhara	2608	2933	12	2385	2861	20
Oromiya	3138	3625	16	3544	4749	34
Somalie	NS	60	—	NS	42	-
Benishangul-Gummez	60	96	59	64	106	65
SNNPR	599	698	16	692	927	34
Gambela	6	10	62	8	23	189
Harari	5	4	-17	6	5	-24
Addis Ababa	10	10	-4	12	15	24
Dire Dawa	10	7	-22	13	5	-68
Total	6960	7949	14	7042	9279	32

† Source, Central Statistical Authority (1996a).
‡ NS, not stated.
§ Southern Nations, Nationalities People's Region.

With the increased use of mineral fertilizer during the 1995-1996 and 1996-1997 crop seasons, Ethiopia recorded its highest harvest of the major crops ever in history. This came about not only as a direct result of increased use of mineral fertilizers but also increased use of improved seed, better extension advice, and favorable rainfall over most of the country (Table 4—3). As can be observed, during the 1995-1996 season, there was an increase of 14% in total area, 32% in production, and 15% in average yields over 1994—1995. Preliminary production estimates of the 1996-1997 season indicate a second consecutive production record for Ethiopia. The 1996-1997 production estimate represents a 21% increase over 1995-1996 revised estimate of 9.7 million tonnes. According to a FAO/WFP (World Food Program) Crop and Supply Assessment Mission who conducted a preharvest crop assessment for the main season; a combination of factors contributed to the bounty of the harvest, including timely and consistent good rains (50% of the production increase because of this), increased area under production (6% over last year) and 20% of the production increase because of the government extension program (FEWS and EU-LFSU, 1996).

All of the cereal crops except wheat have experienced substantial productivity gains (Table 4-^). Wheat yields were reduced because of a stem rust epidemic that completely destroyed the most widely grown wheat cultivar, Enkoy. The experience with stem rust points out the need to strengthen the national wheat research and variety release system in order to (i) broaden the genetic base for disease resistance in future cultivars, and (ii) implement a functional disease surveillance system that will identify changes in pathogen populations early enough so that new resistant cultivars can be released and multiplied to substitute for those that have become susceptible.

The yield gains for millet *[Pennisetum glaucum* (L.) R. Br.] and oat *(Avena sativa* L.) were large (Table 4—4). They, however, are relatively minor crops that

Table *4-4.* Estimates of 1994-1995 and 1995-1996 area, production, and yield of cereal crops for private peasant holdings in Ethiopiai (main rainy season).†

Crop	Total area			Total production			Yield		
	1994-1995	1995-1996	Change	1994-1995	1995-1996	Change	1994-1995	1995-1996	Change
	——1000 ha——		%	——1000 tonnes —		%	——t ha^{M} —		%
Total cereals	5746	6653	16	6154	8270	34	1.07	1.24	16
Tef	1844	2097	14	1298	1752	35	0.70	0.84	19
Barley	879	826	-6	848	873	3	0.96	1.06	10
Wheat	769	882	15	1024	1076	5	1.33	1.22	-8
Maize	1105	1281	16	1673	2539	52	1.51	1.98	31
Sorghum	886	1252	41	1122	1723	54	1.26	1.38	9
Millet	229	269	18	153	241	58	0.67	0.90	34
Oat	35	45	31	36	65	81	1.04	1.45	38

† Source, Central Statistical Authority (1996a).

tend to be planted in marginal areas without fertilizer. When rains are adequate, as in 1995-1996, they can show dramatic increases in production.

Among the major cereals grown in the country, maize had the largest yield gains, with 31%, followed by tef, with 19%. This is to be expected, since these two crops use the bulk of the fertilizer in the country. In spite of the success of participating farmers in raising yields in the demonstration plots, a significant gap still exists between production potential and actual yield among the vast majority of small-scale farmers. The challenge ahead is to convert that potential into reality.

FERTILIZER SECTOR DEVELOPMENT STRATEGIES

In formulating a fertilizer sector strategy for Africa, it is important to understand the nature of industrially produced fertilizer products. Fertilizer manufacturing units are costly to construct and operate, and they must be relatively large in scale and operated near capacity to remain economic. The cost of a typical plant that produces 0.5 million t yr^{-1} of urea or 0.3 million t yr^{-1} of DAP can easily exceed U.S.$300 million (Williams & Schultz, 1990). Because the capacity of these basic production units is so large, few African countries can justify their construction, at least on the basis of domestic demand, even when they have the raw materials at hand. Indeed, among African countries, only Nigeria and South Africa consume >0.25 million product t yr^{-1} (FAO, 1996).

Africa is endowed with numerous phosphate ore deposits, which are a potential source of phosphate fertilizers. With the exception of the export-oriented facilities of Senegal, Togo, Morocco, and Tunisia, few of these deposits have been developed. Some are too small and low in quality for commercial development. But the overriding issue has been limited domestic markets and depressed phosphate prices in the global fertilizer market, which do not justify investment and operating costs. There are, however, some high-quality deposits that are agronomically effective, such as in Mali and Tanzania, where simple processing would make them suitable for direct application to the soil (Buresh et al., 1997, this publication). Use of such deposits should be encouraged.

In most African countries the demand for mineral fertilizer is low but expected to grow appreciably over the next two decades. Thus, the fertilizer supply system should be simple but designed for growth in a stepwise fashion to meet farmers' needs in a timely way. Schultz and Parish (1989) illustrate a stepwise development of a fertilizer supply system to meet growing demand, which seems applicable to Africa. Up to about 100 000 tonnes of annual product demand, importation is almost certain to be the most cost-effective alternative—first in bags and then in bulk. Between 0.1 and 0.2 million tonnes of product demand, local production of granular products becomes a potentially viable enterprise. Above 0.25 million tonnes of product demand, establishing a domestic production unit of world class can be considered, if the raw materials such as natural gas or phosphate rock are available and if there is an assured market for operating the factory at high capacity.

Meanwhile, African countries can benefit from the more favorable economies of large-scale, export-oriented production units in Europe, the USA, North Africa and the Middle East, and elsewhere by importing the required products. Large benefits can be realized by simply performing the marketing functions more efficiently. The landed cost of fertilizer can be decreased by 20 to 40% through relatively simple improvements in procurement systems, such as realistic demand forecasts, selection of appropriate fertilizer types, and consolidation of annual fertilizer requirements into large orders to obtain favorable freight on board (f.o.b.) prices and ocean shipping rates. Additional savings can be achieved by local bagging, local blending of imported materials, and eventually, local granulation.

A cost-effective procurement system should also include unrestricted and timely availability of foreign exchange for procuring fertilizer, and a streamlined procedure of administrative approval that allows the procurement body to respond rapidly and take advantage of favorable supply and demand pricing situations. Properly valued exchange rates also are important. Continually devaluing national currencies work against importing fertilizers and crop protection chemicals, and therefore against modernization.

To lower transport costs, there is an urgent need to shift from low- to high-analysis fertilizers, as Ethiopia has done. For example, the delivered cost of N to African ports can be reduced by about 40% by shifting from ammonium sulfate to urea (Williams& Schultz, 1990). There also are additional savings to be realized on internal freight, warehousing, bagging, and handling. In the Southern African Development Community (SADC) countries alone, Donovan (1996) reports that US$ 100 million can be saved annually—or about 25% of total outlays—by switching to high-analysis grades and bulk handling.

Considerable gains also can be made from improving the effectiveness of research and extension programs in soil fertility management. More area- and crop-specific fertilizer recommendations are needed and, where intensive cropping is practiced, improved monitoring of secondary nutrients and minor element deficiencies. More research also is required to develop integrated practices to restore and manage soil fertility, which can involve both inorganic and organic nutrient sources. National extension services also need to mount mass-education campaigns to teach farmers to use fertilizers in the most efficient manner possible, such as appropriate formulas and combinations of nutrient sources, timely application, optimum planting densities, and timely weed control.

Of course, other developments must come to achieve a more effective fertilizer sector, with improvements in infrastructure high on the priority list. In virtually all African countries more investments are needed in farm-to-market roads to get inputs and outputs in and out of farming areas more efficiently and in trunk roads to link the major cities with the main agricultural producing areas. Over the longer term, low-cost high-volume transportation systems—such as railroad and waterways—must also be given serious consideration. As infrastructure is improved, the cost of using modern agricultural technologies will decline significantly.

IMPROVED SEED IS A NECESSARY COMPLEMENT

Plant breeding is the greatest practical achievement of the biological sciences in the 20th Century. Compared with traditional varieties, today's new food crop varieties are vastly more efficient in grain production, in genetic resistance to diseases and insects, and in tolerance of various agroclimatic stresses than were their predecessor land races. While improved cultivars of maize, rice, wheat, barley, sorghum, tubers, pulses, and oilseeds have been developed by agricultural researchers, too few of these genotypes are reaching African farmers, especially small-scale farmers.

It is very important that African governments look more seriously at the issue of developing the seed industry, as expanded use of improved seed is a necessary condition for a Green Revolution in Africa. As a general principle, seed produced by private enterprises is invariably of higher quality than seed produced by a public sector organization. Thus, future seed industry strategies should have a private sector orientation. But for many crops—especially the food crops grown by smallholders—public sector institutions also will have an important role to play, especially in crop improvement research to develop new varieties and hybrids, in seed certification, and in extension programs to promote rapid diffusion of these more grain-efficient, fertilizer-responsive genotypes. Restoration of soil fertility will help ensure that the potential of improved cultivars is realized.

CONCLUDING REMARKS: THE CHALLENGE AHEAD

Policy planners have failed to fully understand the impact that the introduction of high-yielding food crop technologies can have on reducing poverty and on making agriculture the engine for economic development that it can—and must—become in Africa. In most African countries, basic foods are too expensive rather than too cheap. They are too expensive because of the inefficient, low-yielding technologies that are being employed, which neither provide farmers with adequate incomes nor consumers with food at accessible prices. Farmers can increase their incomes through improvements in productivity and expanded production. More plentiful food supplies lead to lower real prices which, in effect, means increased income for all consumers, but with special benefit for the poor, since most of their income goes to acquire food. Until this reality is understood, and translated into concrete strategies and programs on the ground, the agricultural growth targets of 5 to 6% needed to revitalize African economies and reduce poverty will fall far short of their mark.

There are still influential environmental groups that advocate reliance on organic or *natural* farming in Africa, on the grounds that N fertilizers are harmful to the environment, costly to import and expensive for farmers to use, and in the long run not sustainable because nonrenewable resources are used to produce them. The organic farming advocates, however, fail to recognize that organic sources of N fertilizers generally are very limited and that the release of nutrients to the soil by natural processes usually do not match the time when crops need them. At best, if Asian experience is relevant, reliance on organic fertilizers in

Africa will give 2% yr^{-1} agricultural growth (Hiyami & Ruttan, 1985), well below the rates needed to reduce poverty and improve food security. By all means, let's use organic sources—and local phosphate resources—where practical and cost effective. And let's make sure that sufficient research investments are made to understand how best to combine organic and inorganic nutrient sources. But let's not fool ourselves—there simply isn't enough organic fertilizer to supply sufficient nutrients to the soil to satisfy the growing food demand of Africa.

Agriculturalists and environmentalists certainly both have a professional and moral obligation to warn the political, educational, and religious leaders of the world about the magnitude and difficulties of producing ever-greater quantities of foods to feed the unrelenting *population monster.* But by the same token, we must face up to the fact that we cannot turn back the clock to the *good old days* of the early 1930s, when the world population stood at two billion people and little mineral fertilizer and few agricultural chemicals were used.

Take the USA as an example. In 1940, the production of the 17 most important food, feed, and fiber crops totaled 252 million tonnes from 129 million hectares. Compare these statistics with 1990, when American farmers harvested approximately 600 million tonnes from only 119 million hectares—10 million <50 yr previously. If the USA attempted to produce the 1990 harvest with the technology that prevailed in 1940, it would have required an additional 188 million hectares of land of similar quality. This theoretically could have been achieved either by plowing up 73% of the nation's permanent pastures and rangelands or by converting 61% of the forest and woodland area to cropland. In actuality, since many of these lands are of much lower productive potential than the land now in crops, it would have been necessary to convert a much larger percentage of the pasture and rangelands or forests and woodlands to cropland. Had this been done, imagine the additional havoc from wind and water erosion, the obliteration of forests and extinction of wildlife species through destruction of their natural habitats, and the enormous reduction of outdoor recreation opportunities.

Impressive savings in land use have also accrued to China and India through the application of modern technology to raise yields (Fig. 4-1). Had the cereal yields of 1961 still prevailed in 1992, China would have needed to increase its cultivated cereal area by more than threefold and India by about twofold, to equal their 1992 harvests. Obviously, such a surplus of agricultural land was not available. These lessons of agricultural modernization should not be lost in Africa.

Increasing fertilizer use on food crops from around 5 kg nutrients to 30 to 40 kg ha^{-1} of arable land is surely not an environmental problem but a central component in Africa's environmental solution. It has been amply demonstrated that mineral fertilizers, when properly used, are not only beneficial for productivity enhancement but also are environmentally friendly by permitting production on the same land, and thus prevent the migration of farmers to marginal soils in search of plant nutrients. Increased fertilizer use also should help to reduce soil erosion by increasing plant biomass and vegetative ground cover and, assuming that crop residues are returned to the soil, contribute to improving the organic

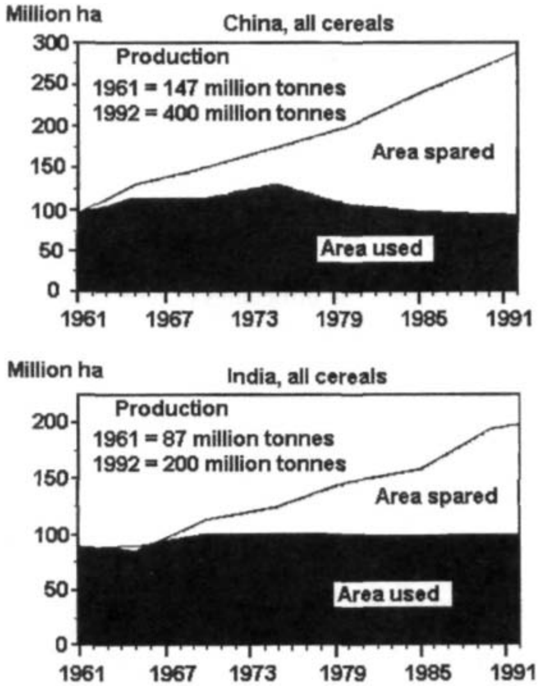

Fig. 4-1. The land spared by Chinese and Indian farmers through raising cereal yields. The upper curve shows the land area needed for 1992 cereal production, had 1961 yields still prevailed; the lower curve shows the land area that was actually harvested (calculated from FAO production data).

matter content of the soil. Obviously, a combination of the two sources of nutrients—inorganic and organic—is more desirable than the use of one source to the exclusion of die other; however, any strategy to achieve 4 to 5% annual agricultural growth in Africa should have as its central component the increased and judicious use of mineral fertilizers, supplemented by organic fertilizer sources; not the reverse.

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5 Soil Profile Alteration under Long-Term, High-Input Agriculture

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ABSTRACT

This chapter presents the findings of several studies that suggest beneficial soil property and characteristic changes from long-term, high-input agronomic methodology. Organic C content declined progressively in unfertilized continuous maize *(Zea mays* L.) plots on Mollisols in the Morrow plots in Illinois until complete fertilization was practiced in 1955. Organic C content in the previously mentioned unfertilized continuous maize plots increased significantly during an 18-yr period after applying lime, N, P, and K at soil test recommended rates. In a Canadian study on Aquolls, soil organic C content was higher after 32 yr of continuous maize in fertilized plots than in similar nonfertilized plots. Two separate studies investigating the long-term effect of erosion on the productive potential of several Mollisols and Ultisols both predict only nominal losses in productivity as a direct result of erosion. Long-term, high-input management of Ultisols in North Carolina significantly increased exchangeable basic cation levels with corresponding decreases in extractable Al levels in subsoil horizons; however, no apparent downward translocation of P was detected. These experiences with high-input agricultural practices in North America can provide an understanding of the long-term consequences and sustainability that such practices could have on similar soils in Africa.

Intensive crop production with modern technology has altered many soils so that they are now more productive. Clearly high-input agriculture has increased the food production per unit of land in the USA since the middle of the 20th century. As seen in Fig. 5-1, chemical fertilization has been one of the factors that have increased efficiency of land area for food production. Concomitant with increased fertilizer use has been mechanization of tillage and harvest operations, improved food storage and distribution, and improved genetics. These practices rely on the availability of raw materials and infrastructure; tints their desirability and sustainability can be debated with regard to social and economic parameters. In this chapter, we address what impacts these practices, in sum termed *high-input agriculture* have had on soil properties. From this review of experience with high-

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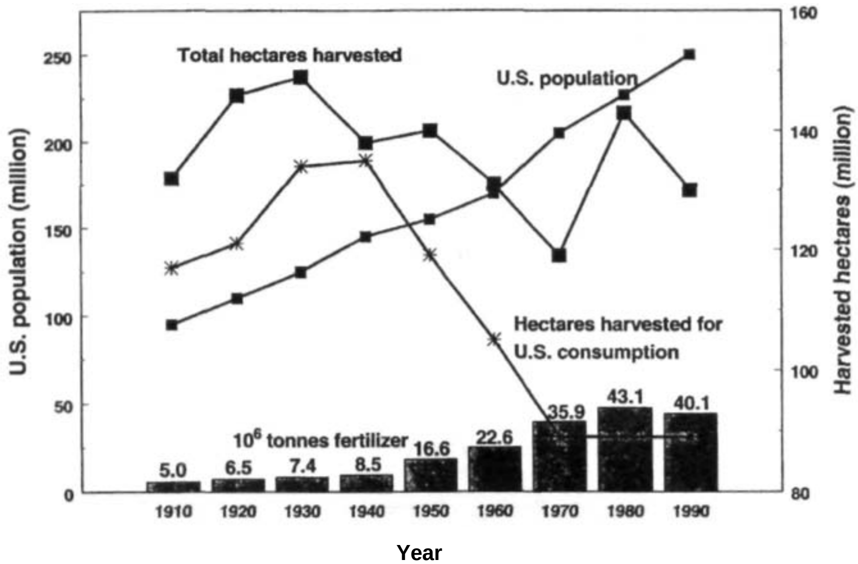

Fig. 5-1. Cropland harvested, fertilizer use, and population in the U.S., 1910-1990 (after Buol, 1995).

input agriculture in North America, scientists in Africa may better understand the long-term consequences and potential sustainability of such practices. The results reported on the long-term effect of lime and fertilizer use on Ultisols that at one time were subjected to slash-and-burn management should have direct application to the evaluation of large areas of Africa with similar acid, low-activity clay soils.

ORGANIC PROPERTIES

One of the best records of continuous crop production in the USA comes from the Morrow plots on the University of Illinois campus at Urbana-Champaign. The plots were established in 1876 on nearly level Flanagan silt loam (fine, smectitic, mesic Aquic Argiudoll) soils (Odell et al., 1982). There was no record of the organic C content of the site when the plots were established, but four samplings of the plots in 1904, 1913, 1923, and 1933 were reported by DeTurk (1938; Table 5-1). He noted that the organic C content progressively declined in the nonfertilized continuous maize, the nonfertilized maize-oat *(Avena sativa* L.) rotation, and the fertilized, limed, and manured continuous maize plots, but did not appear to decline in the maize-oat-clover *(Melilotus alba* L.) rotation and the fertilized, limed, and manured maize-oat rotation plots.

In 1944 the surface soil under the sod around the plots was sampled and compared with the surface soil in the then 68-yr-old plots (Table 5-2). Odell et al. (1982) reported that organic C and total N contents in the continuous, nonfertilized maize plots were lower than in the borders. The limed, manured, and P fertilized maize-oat-clover rotation plots, where the clover crop was not harvested

Table 5-1. Organic C content of surface soil of Morrow plots, west one-half.

	Organic C					
	Continuous maize		Maize-oat rotation		Maize-oat-clover rotation	
Year	No fertilizer	MLP§	No fertilizer	MLP	No fertilizer	MLP
	t ha-1					
1904	47.3	51.3	53.5	49.1	45.7	57.8
1913	45.5		47.7	51.1	47.9	57.3
1923	40.3	48.6	46.6	50.6	49.1	56.0
1933	38.8	47.4	45.0	51.9	46.4	58.1

Source, DeTurk(1938).
Method of organic C analysis not given and may not be comparable with more recent data.
MLP, manure, limestone, and phosphate rock.

tents nearly the same as the plot borders. In 1955, the continuous unfertilized maize plots were split and lime, N, P, and K were applied at rates corresponding to soil test recommendations. This resulted in a significant increase in soil organic C content between 1955 and 1973 even with continuous maize harvest (Fig. 5-2). Darmody and Norton (1994) concluded from micromorphological studies of the Morrow plots that fertilizer and lime inputs had little effect on aggregate properties or soil fabric; however, aggregate stability and macro-pore continuity decreased as intensity of cultivation increased.

Gregorich et al. (1996) found higher organic C contents to a depth of 0.26 m in the fertilized plots after 32 yr of continuous maize with and without N, P, and K fertilization on fine, mixed, mesic Typic Haplaquolls in Ontario, Canada. The difference was accounted for by more Q-derived C in the fertilized soils. They concluded that adequate fertilization not only increased crop yields leading to greater C storage in the soil but did not significantly alter the rate of native soil organic C turnover as determined by ^{13}C studies.

Although a decline in soil organic C content upon cultivation is well documented, there is scant evidence that lower soil organic C contents have any adverse effect on the production potential of the soil. Numerous publications have attributed a decrease in available water-holding capacity to lower soil organic C content. This notion is in part created by the fact that bulk density increases as soil organic C content declines, and cultivation practices tend to compact the sur-

Table 5-2. Organic matter content of the surface soil in and around the Morrow plots in 1944-t

Crop history and treatment	Organic C		Total N	
	t ha-1		t ha-1	%
Sod border (east)	146	100	6.26	100
Sod border (west)	123	85	5.47	87
Maize-oat-clover MLP§	120	82	5.10	81
Continuous maize (no fertilization)	64	44	2.96	47

Source, Odell et al. (1982).
%, percentage of sod border (east).
MLP, manure, limestone, and phosphate rock.

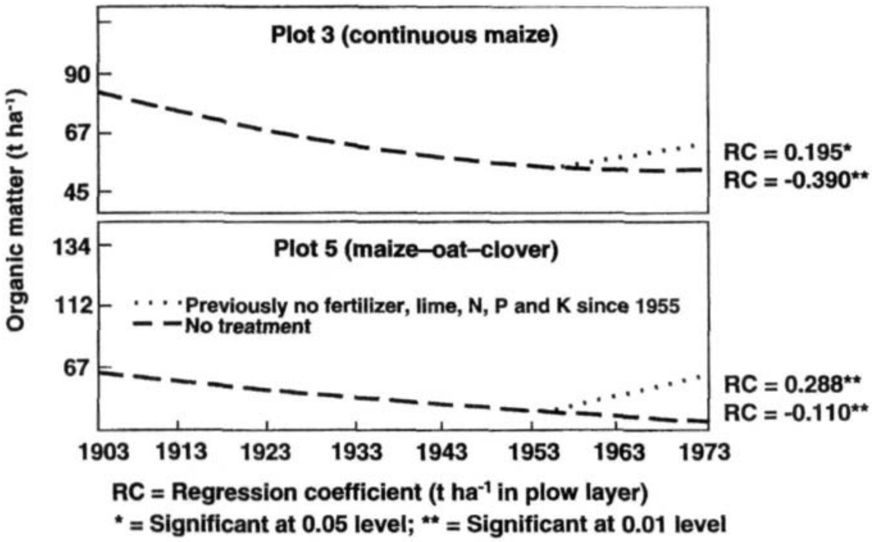

Fig. 5–2. Trends in organic matter content of the plow layer in north blocks of Morrow plots (after Odell et al., 1982).

face horizons. When available water capacity is reported on a soil-weight basis, values increase with increased soil organic C content. When measured on a soil-volume basis, this relationship does not exist. Since plants root in a volume of soil rather than a weight of soil, the volumetric relationship is to be preferred in evaluating the production potential of a soil. Bauer and Black (1992) studied the effect on management-induced changes in soil organic C concentration on the available water capacity of three soil textural groups in North Dakota. Forty-eight sampling locations representing different soil-management systems were selected and sampled in four increments to a depth 0.46 m. All of the soils were Haploborolls or Argiborolls in coarse-loamy, fine-loamy, fine-silty, or fine particle-size families and mixed or smectitic mineralogy families. The bulk density, soil organic C content, and available-water capacity of each sample were then determined, and regression analysis of the data was conducted and presented by particle-size group (Table 5-3). In the medium and fine particle-size samples, available-water capacity, on a volume basis, decreased as soil organic C contents increased. In the sandy soils, available-water content was unaffected by organic C content. They concluded that any decrease in production potential resulting from a decrease in soil organic C content associated with management could not be caused by decreased available-water capacity. Additional studies (Bauer & Black, 1994) reported that decreased crop productivity associated with soil organic C contents resulted from a concomitant loss in fertility, primarily mineralizable N.

Decomposing organic residue does have a positive affect on aggregate stability and infiltration. Bruce et al. (1995) determined that approximately 12 t ha^{-1} yr^{-1} of decomposing mulch was required on the soil surface to significantly increase aggregation and infiltration of eroded Udults in the thermic soil temper-

Table 5-3. Effect of soil organic C concentration on bulk density and available water capacity of three soil textural groups calculated from regressions.†

Soil organic C	Sandy texture		Medium texture		Fine texture	
	BD‡	AWC§	BD	AWC	BD	AWC
g kg^{-1}	Mg m^{-3}	cm cm^{-1}	Mg m^{-3}	cm cm^{-1}	Mg m^{-3}	cm cm^{-1}
10	1.36	0.16	1.31	0.16	1.39	0.21
20	1.16	0.17	1.18	0.13	1.22	0.17
30	0.95	0.16	1.06	0.12	1.05	0.14
40			0.93	0.10	0.92	0.13
50			0.80	0.10	0.81	0.12

† Source, Bauer and Black (1992).
‡ BD, bulk density.
§ AWC, available water capacity.

ature regimes of Georgia. This effect appears related to the binding properties of fungi exudates. Fungi are especially active in decomposing organic residue. The quantity of crop plant residue added to the soil appears to be the most significant organic factor in developing and maintaining a stable surface soil structure (Gantzer et al., 1987); however, it follows that higher rates of organic residue return result in higher quantities of soil organic C if all of the other parameters of soil temperature and aeration are equal.

EROSION

"Under the natural vegetation, especially in humid forested regions, natural erosion serves to maintain a degree of youthfulness and fertility in many soils by removing leached materials from the soil surface while new materials are added to the soil profile from beneath" (Soil Survey Staff, 1951, p. 251). Subsistence farmers without access to fertilizers often concentrate on sloping land, attempting to obtain meager yields from the natural weathering of minerals exposed as surface horizons rapidly erode. Erosion is accelerated as they deplete the fertility by harvesting food products and "if continuing cultivation is assumed, generally, although not always low soil fertility can be regarded as a main cause of erosion" (Soil Survey Staff, 1951, p. 261).

There is no doubt that the intense cultivation and monoculture cropping systems of high-input agriculture also can accelerate erosion rates. The distinction between natural erosion and accelerated erosion is not easy to determine on every soil (Soil Survey Division Staff, 1993). Obviously areas cannot be classified on the basis of what is gone—no longer there. "The mapping standards and guides must be based on characteristics that can be seen" (Soil Survey Staff, 1951, p. 260). "Erosion by itself, unrelated to the [type of] soil, means little or nothing. Tons or inches of soil lost through erosion have little general meaning in terms of soil productivity" (Soil Survey Staff, 1951, p. 268). While amount of soil loss is important to downstream sedimentation, the impact of accelerated erosion, that increment of the total erosion resulting from the cultivation of land, on crop

Table 5-4. Change in production index by slope class for soils in Major Land Resource Area 105 in Minnesota after 25, 50, and 100 yr of erosion.t

Slope	Hectares	Average loss in production index 25 yr	50 yr	100 yr
%			%	
0-2	56 700	0	0	1
2-6	190 755	1	1	2
6-12	91 125	2	3	5
12-20	22 680	10	14	15
20-45	8 505	20	35	56

t Source, Pierce et al. (1983).

production potential must be related to the soil properties remaining after the erosion has taken place. Clearly, each kind of soil is affected differently by erosion.

Pierce et al. (1983) addressed this question by considering the long-term effects of erosion on the productive potential for maize on some Mollisols in Minnesota. They assumed that the soil received good management, which included fertilizer replacement of elements removed in harvest. They considered only the loss in production potential resulting from physical changes resulting in a 1-m-deep root zone as material was eroded from the soil surface at rates currently reported for the respective soils. For Monona soils (fine-silty, mixed, mesic Typic Hapludolis) they projected that an annual erosion rate of 76 t ha^{-1} yr^{-1} would result in a production index reduction of 3% after 100 yr of simulated erosion. Kenyon soils (fine-loamy, mixed, mesic Typic Hapludolis), eroding at a rate of 17 t ha^{-1} yr^{-1} would have a production index reduction of 4% after 100 yr. Rockton soils (fine-loamy, mixed, mesic Typic Argiudolls) would be expected to have a 20% reduction in production index in 100 yr with an erosion rate of 25 t ha^{-1} yr^{-1}. The greater influence of erosion in the Rockton soils results from decreasing the depth to a less desirable root environment in the argillic horizon present in Argiudolls and not present in the more uniform distribution of particle-size with depth in the Hapludolis. When they applied 100-yr projections to the 367 939 ha of cropland in Major Land Resource Area 105 (MLRA 105) in Minnesota they predicted the production index loss, by slope class, after 25, 50, and 100 yr at the present erosion rates (Table 5-4). Clearly the greatest potential loss of production is on the 8.4% of the cropped land with slopes greater than 12%.

The results of Pierce et al. (1983) reflect potential productivity loss on what are considered some of the best soils in the world. The fact that the soils studied are formed in thick loess and glacial till deposits accounts for the small amount of physical change that could be expected as surface soil is eroded and the root zone projected into subsoil material. It could be expected that erosion would more severely decrease the production potential of Ultisols where finer textured argillic and kandic horizons of low base saturation are exposed by erosion of top-soil.

Daniels et al. (1989) intensively investigated crop productivity in fields in the piedmont of North Carolina to determine if the soil properties considered to result from the process of erosion affected crop productivity. The fields they studied had been in cultivation since 1800 or earlier. Although a complete record is not possible, it is probable that the original cultivation was as shifting cultivation, progressing with time to cultivation with animal-powered machines and today conducted by mechanized farming practices, with lime and fertilizer applications becoming common practice prior to 1900. Soils included in the fields studied were classified as Cecil and Georgeville (clayey, kaolinitic, thermic Typic Kanhapludults and Typic Hapludults, respectively) and Cullen and Vance (clayey, mixed, thermic Typic Hapludults). These soils are formed in saprolite weathered from granite, gneiss, and other felsic rocks. Each of the 16 fields studied was traversed while in a vegetation-free state prior to planting, and plots that represented defined erosion classes and landscape position were selected and surveyed relative to identifiable locations. In this way the researchers could identify and compare combinations of soil properties considered to result from erosion and known to influence crop production within comparable landscape positions. The landscape positions identified were linear slopes, nose slopes (convex), head slopes (concave), foot slopes, interfluves, and shoulders. Erosion classes were defined as slight, moderate, or severe according to the amount of B horizon (argillic or kandic) material incorporated into the plow layer. When yields from various crops during a span of 5 yr were summarized they found that soil features considered to be a result of moderate and severe erosion resulted in an economic loss of only US$ 4.44 ha^{-1} yr^{1} based on 1987 prices for crops produced. Although distinct production differences were present among all plots studied, most of these differences were related to landscape position, not to soil property differences attributed to erosion within the same landscape positions. Daniels et al. (1989) clearly found that slightly eroded soils usually out yielded severely eroded soils, but the differences were small and often confounded as a result of weather patterns that exaggerated differences some years, even reversing them in some years. "Because the area of severely eroded soils in most fields is small, their impact on field production is slight" (Daniels et al., 1989).

These results question whether the features usually attributed to erosion have really resulted because of accelerated erosion or whether they are at least in part the result of pedogenesis related to the topographic or relief factor of soil formation (Jenny, 1941). When McCracken et al. (1989) examined a 12-ha tract of virgin land in the piedmont area of North Carolina, with Cecil soils and slopes ranging from 2 to 10%, they found 60% of the area would have considerable amounts of the upper B horizon incorporated into an Ap horizon should the area be plowed. Since incorporation of B-horizon material into the Ap horizon is taken as evidence of erosion, these soils would be identified as borderline moderately eroded even though they had never been cultivated.

Erosion, whether associated with subsistence or intensive agriculture, can severely decrease the production capacity of some soils; however, the experiences cited indicate that degradation of production potential from erosion under high-input management is probably quite modest except on sloping parts of the landscape that have subsoils or parent rock that is not capable of supporting root growth. Unqualified observations indicate that, with the advent of high-input agriculture, steep slopes most subject to severe erosion are often not cultivated because of their incompatibility with the use of large machines so intrinsic to high-input farming. Also, if larger crop plants result from a high input of fertilizer, greater amounts of root and straw residue are produced. It is the decomposition of organic residue that has positive affects on increased aggregation and infiltration (Bruce et al., 1995; Gantzer et al., 1987).

CHEMICAL ALTERATIONS IN ULTISOLS

Intensive crop production on naturally infertile, acid Ultisols requires intensive application of lime and fertilizers to establish an adequate medium for high yields from crop plants, and then to replace nutrients removed at.harvest. Historical records indicate that lime and fertilizers have been used on Ultisols in North Carolina for > 100 yr. Prior to general use of lime and fertilizer, shifting cultivation was extensive in this state. A survey was conducted in North Carolina to ascertain changes in the chemical status of Ultisol profiles as a result of long-term intensive application of lime and fertilizer (M.L. Stokes, 1995, unpublished data).

Three soil cores to a depth of 2 m were taken each from directly adjoining managed and unmanaged areas of a soil map unit. Each core was divided into separate constituent morphological horizons for analysis. The distance between managed and unmanaged sampling points was kept to a maximum of 50 m to minimize spatial variability. Sampled map units were investigated as thoroughly as conditions allowed to confirm that the managed sections had been limed and fertilized for at least 20 yr. The sites reported in this article had been verifiably limed and fertilized as required to obtain maximum potential crop yields for >30 yr. The adjacent unmanaged areas were determined to have not been fertilized for >50 yr by the estimated ages of existing trees. Samples from each horizon were processed for exchangeable base cations, exchangeable Al, soil pH, available P, and total P. Exchangeable base cations were extracted with 1 A/NH_4OAc at pH 7.0 (Soil Survey Laboratory Staff, 1992, p. 146-148). Exchangeable Al was extracted with 1 *M* KC1 (Soil Survey Laboratory Staff, 1992, p. 193-196). Available P was determined by the Bray I extraction method (Soil Survey Laboratory Staff, 1992, p. 218-220). Total P was determined by complete digestion in concentrated H_2S0_4 and H_20_2.

The results presented here are for two soils, a Norfolk sandy loam (fine-loamy, siliceous, thermic Typic Kandiudults) from the coastal plain in North Carolina and a Cecil sandy loam (clayey, kaolinitic, thermic Typic Kanhapludults) from the piedmont in North Carolina. Average yields on Norfolk soils receiving a high level of management are reported as being 6.4 t ha^{-1} for maize and 2.21 ha^{-1} for soybean *[Glycine max* (L.) Merr.; Shaffer, 1994]. Average yields on Cecil soils with similar management are reported as being 6.01 ha^{-1} for maize and 2.2 t ha^{-1} for soybean (Spangler, 1994).

The exchangeable cation extractions, considered from a percentage of saturation basis, indicate a marked increase in percentage of base saturation [($cmol_c$ Ca + Mg + K)/($cmol_c$ Ca + Mg + K + Al) x 100] in the managed sites of both the Cecil and in the Norfolk soils to a depth of 2 m. There is also a decrease in percentage of Al saturation [($cmol_c$ Al)/($cmol_c$ Ca + Mg + K + Al) x 100] in the managed sites of both soils (Fig. 5-3 and *5-4).* Calcium was the major exchangeable

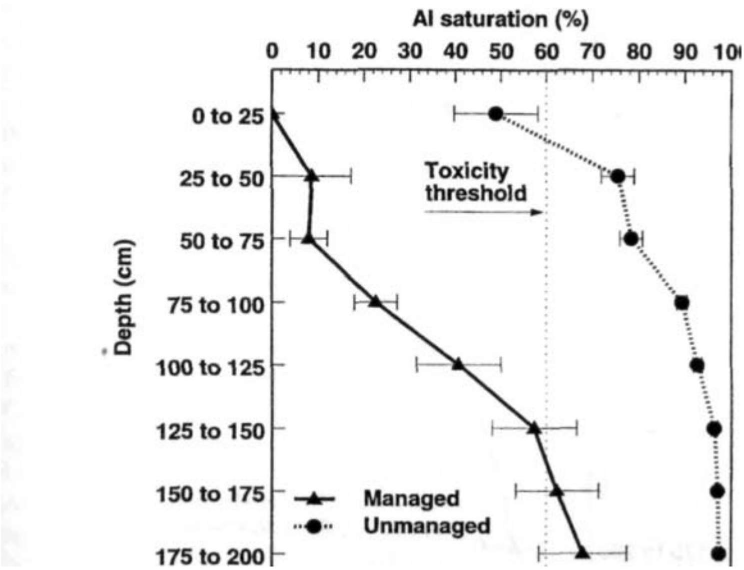

Fig. 5-3. Effect of management on Al saturation for a Cecil sandy loam (2 to 6% slope, eroded, clayey, kaolinitic, thermic Typic Kanhapludults). Data points represent subsampling from entire horizon; error bars represent the standard error of the mean *(P = 0.05)*.

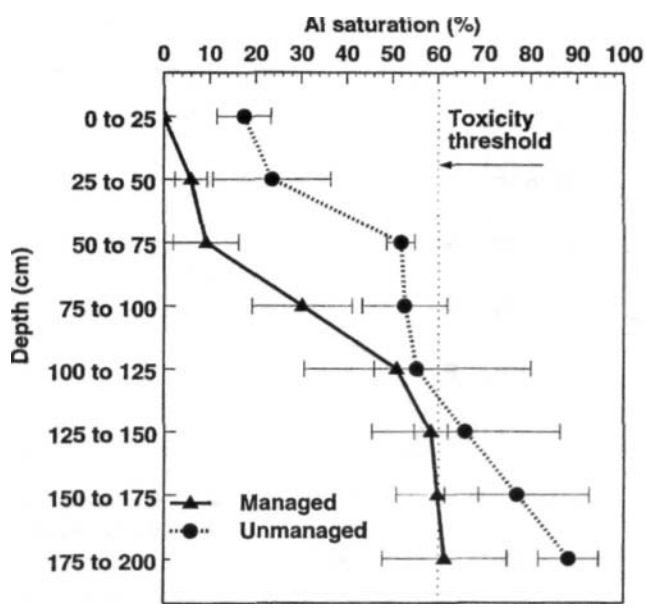

Fig. 5-4. Effect of management on Al saturation for a Norfolk sandy loam (2 to 6% slope, fine-loamy, siliceous, thermic Typic Kandiudults). Data points represent subsampling from entire horizon; error bars represent the standard error of the mean *(P • 0.05)*.

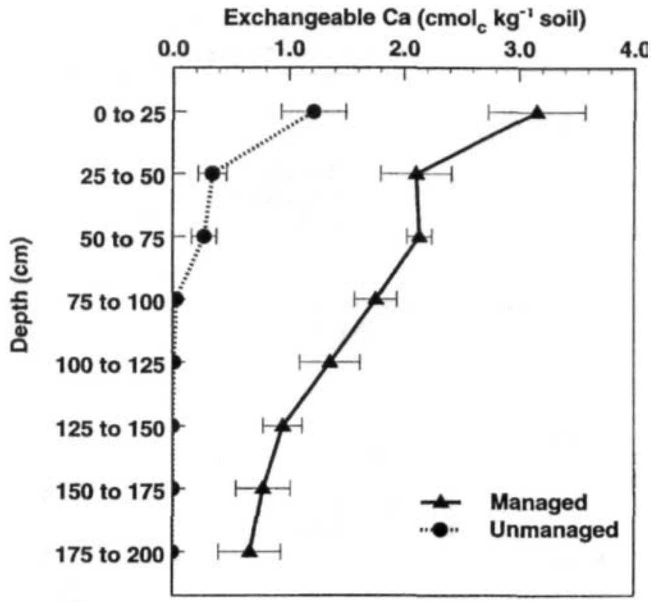

Fig. 5-5. Effect of management on exchangeable Ca for a Cecil sandy loam (2 to 6% slope, eroded, clayey, kaolinitic, thermic Typic Kanhapludults). Data points represent subsampling from entire horizon; error bars represent the standard error of the mean *(P* = 0.05).

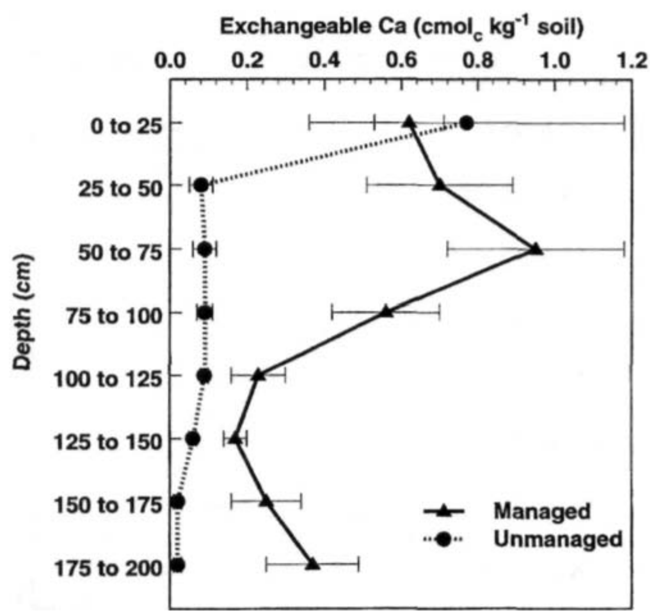

Fig. 5-6. Effect of management on exchangeable Ca for a Norfolk sandy loam (2 to 6% slope, fine-loamy, siliceous, thermic Typic Kandiudults). Data points represent subsampling from entire horizon; error bars represent the standard error of the mean *(P* = 0.05).

base cation component of the base saturation levels in all soils and was observed to have a dramatically greater accumulation in managed sites (Fig. 5-5 and 5-6) from the surface to a depth of 2 m. The apparent increase in the surface horizon of the Norfolk (Fig. 5-6) is due to an uncharacteristically large amount of Ca in the surface horizon of one of the cores from the unmanaged site as evidenced by the large error bar. Exchangeable Mg contents were found to mimic exchangeable Ca trends in both soils. Dolomite is the most commonly used liming material.

Exchangeable K contents had little to no observable trends in either managed or unmanaged soils. Extractable Na only appears in trace amounts in these soils.

Total P contents were greater in the surface horizons of the managed sites reflecting long-term accumulation of fertilizer P (Fig. 5-7 and 5-8); however, from 0.75 to 1.5 m in the Norfolk and from 0.5 to 0.75 and 1.25 to 1.5 m in the Cecil, the levels of total P were lower in the cultivated sites than in the unmanaged sites. We hypothesize that this has resulted from the extraction of subsoil P by crop roots active at these depths as a result of diminished levels of extractable Al. Available P contents below the surface horizons in both managed and unmanaged sites were too low to report effectively. The only substantial differences between the two soils was in total amounts of extractable constituents with greater amounts extracted from the clayey, kaolinitic soils than from the fine-loamy, siliceous soils. A reduction in the adverse effects of short-term drought could be expected to result as plant roots are exposed to more available water as the effective rooting depth deepens from the reduction in extractable Al, but we have no measurements to verify this effect.

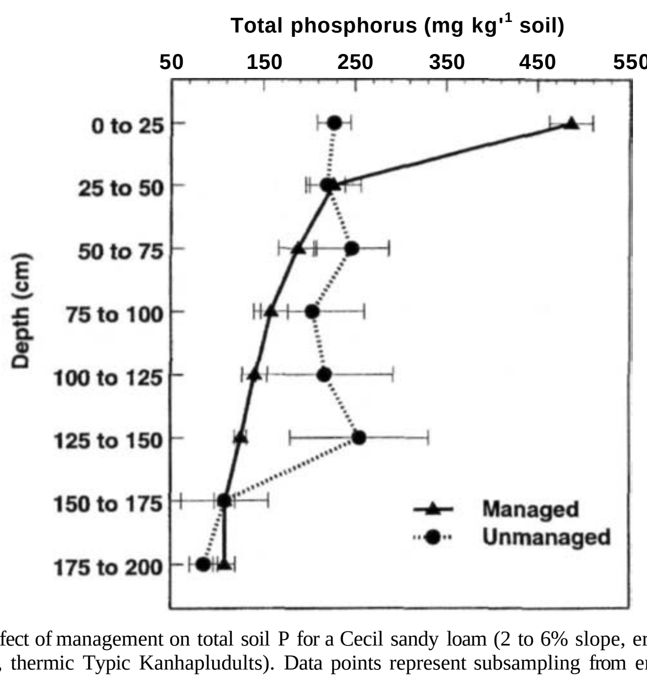

Fig. 5-7. Effect of management on total soil P for a Cecil sandy loam (2 to 6% slope, eroded, clayey, kaolinitic, thermic Typic Kanhapludults). Data points represent subsampling from entire horizon; error bars represent the standard error of the mean (P = 0.05).

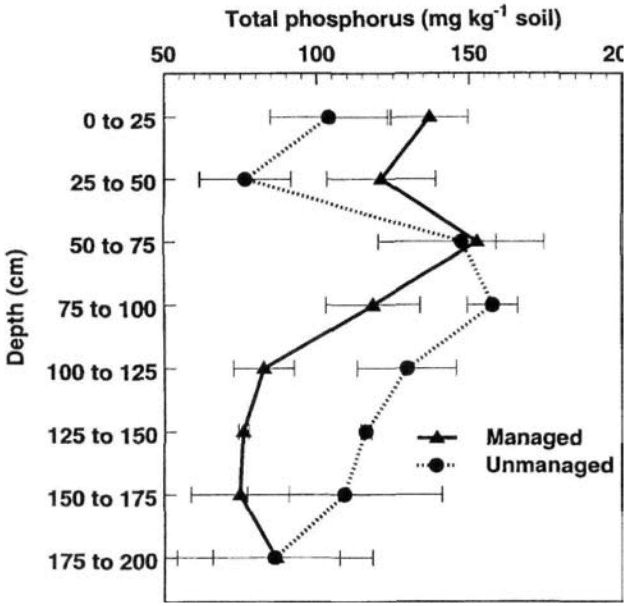

Fig. 5-8. Effect of management on total soil P for a Norfolk sandy loam (2 to 6% slope, fine-loamy, siliceous, thermic Typic Kandiudults). Data points represent subsampling from entire horizon; error bars represent the standard error of the mean *(P* = 0.05).

CONCLUSIONS AND SUMMARY

High-input agriculture allows agricultural concentration on the soils least subject to degradation where, with replenishment of nutrients harvested, production is sustainable indefinitely (Loomis, 1984). While Loomis reached this conclusion from data derived in large part from fertile Mollisols and Alfisols, our more recent work clearly indicates substantial improvement in soil properties related to crop production resulting from long-term, high-input management of naturally infertile Ultisols. High erosion rates are a cause for concern because agricultural production potential is determined by the quality of the remaining soil. Organic C contents that become lower under inadequate fertilization appear to recover when adequate fertilizer is applied. Adequate fertilization also contributes to greater biomass production tending to protect soil from erosion and providing greater quantities of residue critical to soil aggregation. We therefore conclude that long-term, high-input agriculture has had a strong positive affect in improving agronomic properties of soils.

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Building Soil Phosphorus Capital in Africa

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ABSTRACT

Cropping with little or no P inputs has depleted soil P stocks in sub-Saharan Africa. Phosphorus is now a limiting nutrient in many sandy soils of the semiarid tropics and in acid, weathered soils of the subhumid and humid tropics. Replenishing P stocks in highly P-deficient soils requires input of P fertilizers rather than sole dependence on P cycling through organic-based systems. The soil P stock that serves as a major sink for added P and gradually releases plant-available P for up to 10 yr is referred to as *soil P capital.* It is comprised of inorganic P sorbed on clays and Fe and Al oxides and P in organic pools. Soil P can be replenished with either soluble P fertilizers, direct application of sufficiently reactive phosphate rock (PR), or the combination of soluble P fertilizer and PR. Phosphorus can be replenished either immediately with a large, one-time P application or gradually with moderate seasonal applications of P at rates sufficient to increase availability of soil P. The P rate required to overcome P deficiency increases with increasing P-sorption capacity of the soil, and the residual benefit from added P increases with increasing P sorption, except for soils with allophane. An initial, large corrective P application followed by maintenance applications of P can rapidly replenish and maintain soil P capital. The replenishment and subsequent maintenance of soil P must be accompanied with management to overcome other nutrient limitations and crop growth constraints to ensure sustained crop production at increased levels without environmental degradation.

Many soils in sub-Saharan Africa (hereafter referred to as Africa) are characterized by deficient levels of plant-available P. Despite diversity in distribution of parent material and conditions affecting soil formation, soil P deficiencies primarily result from either inherent low levels of soil P or depletion of soil P. In

 Replenishing Soil Fertility in Africa. SSSA Special Publication no. 51.

much of the semiarid zone, soils were derived from acidic parent material that contained low levels of P. For the once P fertile soils (e.g., soils of the highlands of East Africa), on the other hand, soil P stocks have decreased as increasing population has led to replacement of traditional systems of shifting cultivation with shorter duration unsustainable fallow systems and sedentary agriculture. Many smallholder farmers have lacked the financial resources to purchase sufficient fertilizers to either correct inherent low levels of soil P or replace the P exported with harvested products (World Bank, 1994; Sanchez et al., 1997, this publication). This factor has been a major component of the overall depletion of soil fertility and the resulting degradation of soil resources.

There is an indisputable need to correct deficiency of soil P in Africa (World Bank, 1994; Mokwunye et al., 1996; Smaling et al., 1997, this publication). Numerous studies in Africa have shown that P fertilizers—including ground PR, modified PR products, and soluble sources, such as triple superphosphate (TSP) and single superphosphate (SSP)—can significantly increase crop yields (Wild, 1973; Le Mare, 1984; Sale & Mokwunye, 1993). Relatively small seasonal applications of soluble P fertilizer can mitigate P deficiency in soils with low to moderate P-sorption capacity; but larger rates of soluble P are required for soils with higher P-sorption capacity.

In view of this situation, there has been a call for the replenishment of soil fertility as a capital investment in Africa (World Bank, 1994; Sanchez et al., 1996, 1997, this publication). The replenishment of soil P fertility implies building soil P stocks to levels at which P is not limiting. After P is added to soil, it can be sorbed onto clay and oxide surfaces or converted to organic P and then gradually released as plant-available P for a number of years. The stock of soil P that gradually supplies plant-available P to crops for about 5 to 10 yr has been referred to as *P capital* (Sanchez & Palm, 1996).

The replenishment of soil P capital can be achieved either rapidly through a one-time investment in a large P application or gradually through seasonal applications of P at rates sufficient to increase P availability. The replenishment of soil P capital, in combination with management to overcome other nutrient limitations and crop growth constraints, would provide benefits of increased crop production and income to farmers as well as environmental benefits to society (Izac, 1997, this publication). After replenishment of soil P with a large, one-time investment, only moderate inputs of P would be required to maintain P fertility. The combination of P replenishment with N replenishment can have synergism. For example, the elimination of P deficiency can enhance N_2 fixation by legumes (Cassman et al., 1993; Giller et al., 1997, this publication), and the integrated use of P fertilizers with organic materials to supply N and K can potentially enhance P availability (Palm et al., 1997, this publication).

This chapter will review (i) soil P pools and transformations in relation to the concept of P capital, (ii) sources of P including indigenous PR, (iii) the potential of organic materials and agroforestry to supply P, (iii) the management and economics of P sources, and (iv) conditions conducive for investment in the rapid replenishment of soil P. The review will be limited to annual food crops.

SOIL PHOSPHORUS POOLS

Inorganic Phosphorus

Phosphorus occurs in soil in inorganic and organic forms, which vary in their rate of P release (Fig. 6-1). The original soil source of soluble inorganic P (Pj) is dissolution of primary P minerals, mainly apatite. Primary P minerals decrease in soil with increasing soil weathering and are relatively unimportant in highly weathered soils (Smeck, 1985). Once in the soil solution, P_i can be (i) taken up by plants, (ii) taken up by soil biota and converted to organic P (P_0), and (iii) sorbed onto soil minerals. Labile P_i is loosely sorbed and in rapid equilibrium with soil solution Pj, whereas strongly sorbed P_i is only slowly released and made available to plants.

In acid soils without allophane, the sorption of P_i occurs mainly on hydrous oxides of Fe and Al at the surface of layer-silicate clay particles (Schwertmann & Herbillon, 1992; Frossard et al., 1995), which increase in importance in soils with increased weathering and clay content (Sanchez & Uehara, 1980). Numerous studies have shown that P sorption is directly related to the contents of clay and oxides of Fe and Al in soil (Juo & Fox, 1977; Loganathan et al., 1987; Owusu-Bennoah & Acquaye, 1989). Phosphorus sorption is a dominant process controlling P availability in Ultisols and Oxisols with medium- and fine-textured topsoil (Sanchez & Uehara, 1980), which are major soils in the humid and subhumid tropics of Africa (Deckers, 1993). Phosphorus sorption is of minor importance in sandy soils that are predominant in the semiarid tropics of Africa (Doumbia et al., 1992). Volcanic soils with amorphous alumino-silicates and humus-Al complexes have a very high capacity to sorb P. This sorption tends to

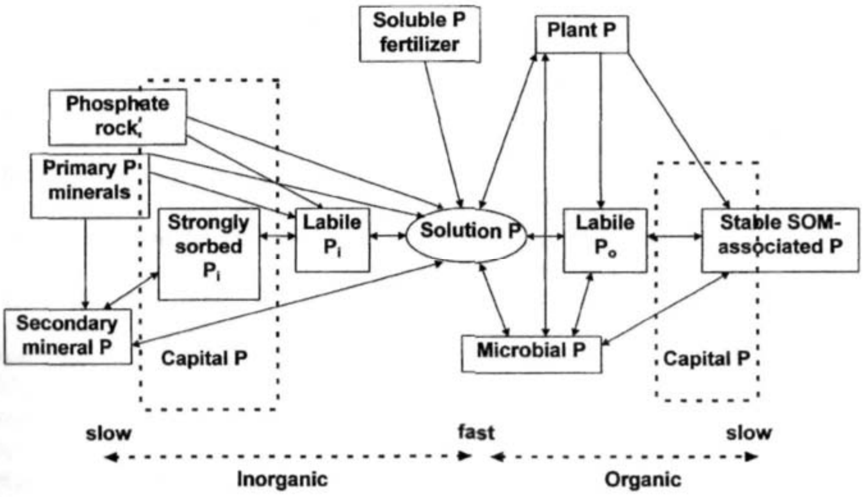

Fig. 6–1. Conceptual diagram of soil P pools and P dynamics following application of phosphate rock and soluble P fertilizer (adapted from Stewart & Sharpley, 1987).

be essentially irreversible, and even high rates of P application do not satisfy the P-sorption capacity (Espinosa, 1992).

Inorganic P along the continuum of decreasing rate of release to solution P_i (Fig. 6-1) can be distinguished through sequential P fractionation with resin, sodium bicarbonate, sodium hydroxide (NaOH), and hydrochloric acid (HC1; Hedley et al., 1982; Tiessen & Moir, 1993). Resin-extractable P_i is directly exchangeable with the soil solution, and bicarbonate-extractable P_i is loosely sorbed. Both fractions represent labile Pj. NaOH-extractable P_i is strongly sorbed onto Fe and Al oxides and clay edges and is only slowly available to plants. Dilute HCl-extractable P_i represents P from calcium phosphates, which comprise a large portion of total P_i on young soils but are relatively unimportant on highly weathered soils unless these soils are amended with PR (Tiessen & Moir, 1993; Cross & Schlesinger, 1995).

The NaOH P_i fraction increases in importance with increased soil weathering due to increased Fe and Al oxides and sorption of P. NaOH P_i was the dominant fraction related to availability of P to plants in an 18-yr continuously cultivated and fertilized cropping system on an Ultisol (Beck & Sanchez, 1994). NaOH P_i appears to include a slowly labile P_i pool, which is an important source of available P within the time frame of 2 to 10 yr. Studies on Ultisols fertilized with P for 4 yr (Linquist et al., 1997a) and 10 yr (Schmidt et al., 1996) found that the bicarbonate P_i and NaOH P_i fractions were sinks for fertilizer P applied in excess of plant uptake. The amounts of P in these fractions decreased after discontinuation of P fertilization, indicating that the fractions represented sources of plant-available P.

Organic Phosphorus

Inorganic P in soil solution is partly replenished by mineralization of P_0. Total P_0 decreases with continuous cropping without P fertilization (Jones, 1972; Adetunji, 1994), and total P_0 as a fraction of the total soil P tends to increase with soil age (Walker & Syers, 1976; Cross & Schlesinger, 1995). Total P_0 is lower in sandy soils common in the semiarid tropics than in medium- and fine-textured soils. Only a small fraction of total soil P_0 is labile in the short term; the vast majority of soil P_0 occurs in stabilized soil organic matter (SOM) and is not rapidly mineralized (Fig. 6-1).

Use of available soil P by plants and soil biota is the driving force for the conversion of P_i to organic compounds and the subsequent mineralization of P_0 (Dalai, 1977; Stewart & Tiessen, 1987). Much of the P associated with soil biota is contained in bacteria and fungi. Amoebae, nematodes, and soil fauna generally contain only a small fraction of the P in soil biota, but they can be very important in the mineralization of P_0 and the availability of P (Frossard et al., 1995). The P_0 concentration can exceed P_i concentration in soil solution due to lower sorption of P_0, and P_0 can be the main form in which P moves in soil (Frossard et al., 1989). Brouwer and Powell (1995) reported that P from relatively large inputs of cattle manure can be leached below the rooting depth of crops on Psammentic Paleustalfs (85 to 90% sand).

Sodium bicarbonate and sodium hydroxide are two extractants commonly used in attempts to isolate labile P_0. Bicarbonate P_0 contains labile compounds that are easily mineralizable to plant-available P (Bowman & Cole, 1978). Anion-exchange resin has also been used to extract labile P_0 (Rubaek & Sibbesen, 1993; Andersohn, 1996). NaOH P_0 contains P associated with humic compounds and P sorbed to Fe and Al oxides (Cross & Schlesinger, 1995). NaOH P_0 is more stable than bicarbonate P_0, but it can be an important P source for soil microorganisms, especially when labile P; is low (Chauhan et al., 1981).

In a comparison of fallow and cropping systems on an Oxisol in Brazil, the bicarbonate P_0 fraction remained relatively constant regardless of cropping history, whereas the NaOH P_0 fraction reflected changes in SOM due to cultivation (Tiessen et al., 1992). Beck and Sanchez (1994) concluded for an nonfertilized, 18-yr cropping system on an Ultisol in Peru that NaOH P_0 was the dominant source of plant-available P. In fertilized systems, an the other hand, NaOH Pj was the dominant fraction related to plant availability of P. Maroko et al. (ICRAF, 1996, unpublished data) measured NaOH P_0 without preceding resin and bicarbonate extractions, after a 1.5-yr nonfertilized sesbania *[Sesbania sesban* (L.) Merr.] tree fallow, a 1.5-yr uncultivated natural fallow, and nonfertilized maize *(Zea mays* L.) monoculture on a Kandiudalific Eutrudox with low labile P; (bicarbonate-extractable Pj = 2 mg kg^{-1}) in Kenya. NaOH P_0, which included bicarbonate P_0, differed among the fallow and maize systems, whereas bicarbonate P_0 and P_i were not affected by the systems. NaOH P_0 without bicarbonate P_0, as determined by difference between the two pools, was affected by the systems *(P* <0.05).

In summary, NaOH P_0 appears to represent a slowly labile P pool, which is an important source of mineralizable P_0 within the time frame of 2 to 10 yr in tropical soils. Tiessen et al. (1994), however, cautioned that the term labile, as associated with specific extractants, should not be universally applied to tropical and temperate soils and to short and long time frames. Moreover, the P measured in specific extracts is not exactly congruent with P in conceptual pools illustrated in Fig. 6-1 (Gijsman et al., 1996).

SUPPLY OF PLANT-AVAILABLE PHOSPHORUS

Inorganic Phosphorus

The supply of P from P_i to plants depends on (i) the concentration of P_i in soil solution, (ii) the quantity of solid-phase P_i that serves as a reserve to replenish P in soil solution, and (iii) the ability of the soil to maintain the solution P concentration (Holford, 1997). A portion of the P_i sorbed by Fe and Al oxides can be reversibly released to replenish P, in soil solution, although desorption of P_i is slower than sorption of P_i (Barrow, 1983). Desorption of P in a soil is inversely related to the duration of P sorption, content and form of Fe and Al oxides in the soil, soil P-sorption capacity, and the portion of soil-sorbing capacity that is unoccupied (Frossard et al., 1995). Some organic compounds, such as oxalate and malate, can desorb P through competition with P-sorption sites and complexation of Fe and Al ions in acid soils containing Fe and Al oxides (Lopez-Hernandez et al., 1986; Hue, 1991; Fox & Comerford, 1992).

The supply of P_i to plants is usually estimated by extractive tests that measure the P_i in solution and an amount of labile P_i. Chemical extractants, however, do not consider the kinetics of P_i sorption and desorption, which can strongly influence the supply of P to plants (Kuo, 1990; Raven & Hossner, 1994). The inclusion of an index of P sorption with chemically extracted P_i can improve the estimation of P availability (Indiati & Sharpley, 1996). The content of soil clay within a region of similar parent material is one such index of P sorption. The inclusion of clay content with extractable P_i improved the prediction of P fertilizer requirements on soils in Brazil (Lins et al., 1985; Lins & Cox, 1989). Recovery of P fertilizer by upland rice *(Oryza sativa* L.) was inversely related to the silt plus clay content of acid soils in Cote d'lvoire (Van Reuler, 1996). This use of clay content appears effective on soils with predominantly kaolinitic clay, in which Fe and Al oxide content is directly related to the clay content. It will not be effective on soils with free calcium carbonate or P sorption by amorphous alumino-silicates and humus-Al complexes (Cox, 1994).

The critical concentration of extractable P required for a given quantity of P uptake by a plant decreases with increasing P sorption. Cox (1994), for example, showed that the critical P level with Mehlich-3 extractable P was 22 mg P L^{-1} for soil with low P sorption (10% clay) and 13 mg P L^{-1} for a soil with higher P sorption (25% clay).

Phosphorus sinks, such as resins and Fe-oxide impregnated paper (Sharpley et al., 1994; Menon & Chien, 1995; Menon et al., 1997), and isotope exchange (Fardeau et al., 1996; Morel et al., 1996; Di et al., 1997) generally estimate P availability to plant roots more closely than do chemical extractants. Lins and Cox (1989), however, showed that the inclusion of an index of P sorption (clay content) with even resin-extractable P increased the predictability of P supply.

Organic Phosphorus

Net mineralization of P_0 is generally directly related to total soil P_0 for both fertilized and nonfertilized soils (Sharpley, 1985). Net mineralization of P_0, therefore, tends to be more important as a source of plant-available P on highly than slightly weathered soils because of the generally greater total P_0 in highly weathered soils (Tiessen et al., 1984; Sharpley et al., 1987).

Early research on soils from Kenya (Friend & Birch, 1960) and southern Nigeria (Adepetu & Corey, 1976) revealed a strong direct relationship between total soil P_0 and plant-available P. The mineralization of P_0 can raise P_i in soil solution, but the P_i can be rapidly sorbed on Fe and Al oxides (Adepetu & Corey, 1977). Declines in total SOM, as traditional rotational systems containing fallows are replaced by continuous cropping, can lead to reduced supply of plant-available P from mineralization of P_0 and thus greater need for external inputs of P.

The cycling of P_0 to plant-available P is a function of the size and activity of the microbial biomass (Stewart & Tiessen, 1987), which in turn are governed by the supply of available C and nutrients. In many ecosystems including smallholder farms in Africa, C is the factor most limiting microbial biomass and rapid nutrient turnover (Smith, 1994). The cycling of P through plants and soil biota can consequently be closely linked with C cycling (Huffman et al., 1996). In highly P-deficient soils with a wide range of C-to-P ratios in organic pools, however, the relationship between P and C cycling may be less closely linked (Gijsman et al., 1996).

Possible indicators of P_0 dynamics and conversion of P_0 to P; include microbial biomass, biologically active SOM, and inputs of mineralizable organic material (Tiessen et al., 1994). Maroko et al. (ICRAF, 1996, unpublished data) found that microbial biomass P and P associated with light-fraction SOM differed among an nonfertilized tree fallow, an uncultivated natural fallow, and continuous maize after 1.5 yr on an Eutrudox with low labile Pj. Microbial biomass P and light-fraction P also were each correlated with yield of subsequent nonfertilized maize (ICRAF, 1996, p. 69-70; ICRAF, 1996, unpublished data).

Bowman and Cole (1978) proposed that the sum of bicarbonate P_i and P_0 would be a better indicator of plant response to P than bicarbonate P_i alone, especially for soils low or deficient in P based on bicarbonate Pj. Soils with low bicarbonate P_i and much higher bicarbonate P_0, however, can be responsive to P fertilizer. An Eutrudox in western Kenya with 1 to 3 mg bicarbonate P_i kg^{-1} and 11 to 15 mg bicarbonate P_0 kg^{-1} in the top 15-cm soil layer, for example, was highly responsive to P (J. Maroko, ICRAF, 1996, unpublished data). In contrast to other findings on acid soil without P fertilization (Linquist et al., 1997a), bicarbonate P_0 was not related to maize yield. This observation suggests that a portion of the bicarbonate P_0 was not readily mineralizable.

The importance of P„ as a source of plant-available P might explain the poor correlations between crop response to applied P and P extracted by conventional soil P tests that do not assess P_0 (Warren, 1992; Tiessen et al., 1994). Such poor correlations could arise when the mineralization of P_0 supplies sufficient plant-available P to match or exceed the shortfall in P release from labile P_i to meet plant demand for P. When labile P_i supplies sufficient P to meet plant demand, the combination of an indicator of P availability from P_0 with extractable P_i did not improve the correlation with plant growth (Mnkeni et al., 1995). Extractable P_i together with a labile P_0-to-labile P_i ratio, might be valuable in assessing the importance of P_0 mineralization. The relative importance of P_0 mineralization, compared with desorption of Pj, as a source of plant-available P would presumably be greatest at low extractable $P_{i;}$ high labile P_0-to-labile P_i ratio, and high microbial P.

PLANT EXTRACTION OF SOIL PHOSPHORUS

Plants differ greatly in their ability to grow on soils with low P status and to respond to P inputs (Sanchez & Salinas, 1981). These differences are related to the efficiency of plants to take up and use soil P. Factors affecting uptake of P include the abilities of plants (i) to absorb P from low soil solution concentrations, (ii) to explore a large soil volume, (iii) to solubilize soil P_i through pH changes and the release of chelating agents, and (iv) to release phosphatase enzymes (Kirk et al., 1993; Lajtha & Harrison, 1995).

The solution P concentration required for optimum growth varies among plants (Sanchez & Uehara, 1980). A value of 0.2 mg P L^{-1} has been used as a *standard* solution concentration for comparing P sorption of different soils (Juo & Fox, 1977), but it should not be viewed as applicable to all crops. Moreover, its use as an indicator of P requirements can result in higher P applications than required for maximum crop yield. The uptake of soil P can be enhanced through association of plant roots with mycorrhizas. The extensive proliferation of mycorrhizal hyphae enables the exploration of a greater soil volume (Lajtha & Harrison, 1995).

The availability of soil P can be increased by organic acids and acid phosphatases exuded by plant roots (Delhaize, 1995; Randall, 1995) and by plant-induced changes in soil pH (Marschner, 1995). Organic acids in root exudates can complex Fe and Al, resulting in release of P bound by Fe and Al oxides (Ae et al., 1990; Otani et al., 1996). Hedley et al. (1994) reported that most soil P taken up by rice as a result of root-induced changes in soil pH and release of P-solubilizing agents was from NaOH P_i. Gahoonia and Nielsen (1992) found root-induced depletion of both NaOH P_i and P_0 by rape *(Brassica napus* L.), suggesting that short-term mineralization of P_0 in the rhizosphere supplied P to the plant. The secretion of H^+ and acidification of the rhizosphere are greater for legumes, which accumulate N through symbiotic N_2 fixation rather than through uptake of nitrate (De Swart & Van Diest, 1987).

SOIL PHOSPHORUS CAPITAL

Sanchez and Palm (1996) tentatively defined *soil P capital* as the stock of soil P that gradually supplies plant-available P for about 5 to 10 yr. This stock was referred to as *reserve capital P* by Baanante (1998), but authors in this publication (Izac, 1997, this publication; Sanchez et al., 1997, this publication) simply refer to it as *capital P.* Sanchez et al. (1997, this publication) highlighted that the P fluxes from capital P to P taken up by a crop during a growing season are synonymous to the concept of *service flows* in economics.

The element of time is important in the definition of P capital because there is a component of *inert P* that does not become available to plants within a reasonable time frame, which for the purposes of this chapter is defined as 10 yr. Efforts to improve capital P also will contribute to the inert P pool. The goal of replenishing soil P is, therefore, not to maximize soil P stocks. Instead, the goal is to increase capital P to a size that results in service flows sufficient for crop production without P limitations for several seasons (Sanchez et al., 1997, this publication).

The P available to crops within one season was referred to as *liquid capital P* by Baanante (1998), but it is not *capital P* as defined by Sanchez and Palm (1996) and Sanchez et al. (1997, this publication). In this chapter, *liquid P* will be used to refer to soil P available to crops within one growing season. Liquid P includes service flows, the flux of P from capital P, as well as a portion of the P added in the cropping season as mineral fertilizers (hereafter referred to as inorganic fertilizers) and organic materials. When inorganic P fertilizers and organic materials are not added in the cropping season, capital P supplies the P taken up by crops. In that case, service flows and liquid P are synonymous.

Capital P includes sorbed P, a portion of the primary P minerals, and a portion of the stable SOM-associated P (Fig. 6-1). Although no extractant will precisely quantify capital P, NaOH P_i and P_0 as determined by sequential extraction presumably contain P that gradually becomes available for plant use over several cropping seasons. Liquid P is presumably approximated by labile P_i and P_0, microbial P, and soil solution P. Microbial biomass P and the sum of sequential extractions with resin and bicarbonate presumably approximate a pool that is readily available for plant uptake; however, only the portion of bicarbonate P_0 that is mineralized within one season would represent liquid P.

A portion of PR-P added to soil, depending upon soil properties and the reactivity of the PR, becomes available for plant uptake over a number of cropping seasons. The undissolved PR that gradually releases P for up to 10 yr to liquid P represents capital P not detected by NaOH extraction. The P dissolved from PR like P from any water-soluble P source, is subject to conversion to plant-unavailable P forms due to reactions with soil components such as Al and Fe oxides (Fig. 6—1).

The contribution of capital P to crop production depends not only on its size but also on the rates and magnitudes of P flows among soil P pools and on the ability of plants to take up and efficiently use soil P. These flows might also be influenced by soil aggregation. Linquist et al. (1997b), for example, reported that an increase in size of soil aggregates can increase availability of applied P to plants through reduction in sorptive surface area.

REPLENISHING SOIL PHOSPHORUS CAPITAL

Organic-Based Systems and Agroforestry

Relatively large additions of high-quality organic materials can increase liquid P and capital P. Addition of 5.51 dry matter ha"^{1} of tithonia *[Tithonia diversifolia* (Hemsley) A. Gray] biomass, equivalent to 15 kg P ha^{-1}, to a Kandiudalf in Kenya increased resin P and NaOH P; at 2 to 16 wk after application (Nziguheba et al., 1998). This observation is consistent with earlier reports that tithonia was an effective source of nutrients, including P (Nagarajah & Nizar, 1982).

Low-quality organic materials (see Palm et al., 1997, this publication), however, might be ineffective sources of plant-available P. Application of maize stover equivalent to 15 kg P ha^{-1}, for example, had little effect on resin P and no effect on NaOH P_i in 16 wk, apparently because maize stover has less soluble P_i and slower decomposition than tithonia (Nziguheba et al., 1998).

Even though some organic materials have the potential to increase liquid P and capital P, the amount of P that can be added through organic materials is restricted by the limited supply of organic materials at the farm level (Palm et al., 1997, this publication). For example, application of 18 kg P ha-^{1}, the approximate amount of P used by a 2 t ha^{-1} maize crop (Palm, 1995), would require application of 6 t dry matter ha^{-1} of organic material containing 3 g P kg^{-1}. Low available soil P, however, can limit the production of plant biomass for use as organic inputs. Organic materials also frequently have a higher N-to-P ratio than the ratio required by crops (Palm, 1995). Jama et al. (1997) found in western Kenya, that rather than using organic material with a high N-to-P ratio to supply all the P required by maize, it was economically more attractive to integrate TSP with the organic material, whereby the organic material provided the required N for the crop and the TSP met the additional requirement for P. Integrated application of inorganic P fertilizer with organic material would have an agronomic advantage compared with sole application of inorganic P, if the organic material enhanced the availability of added P (Palm et al., 1997, this publication).

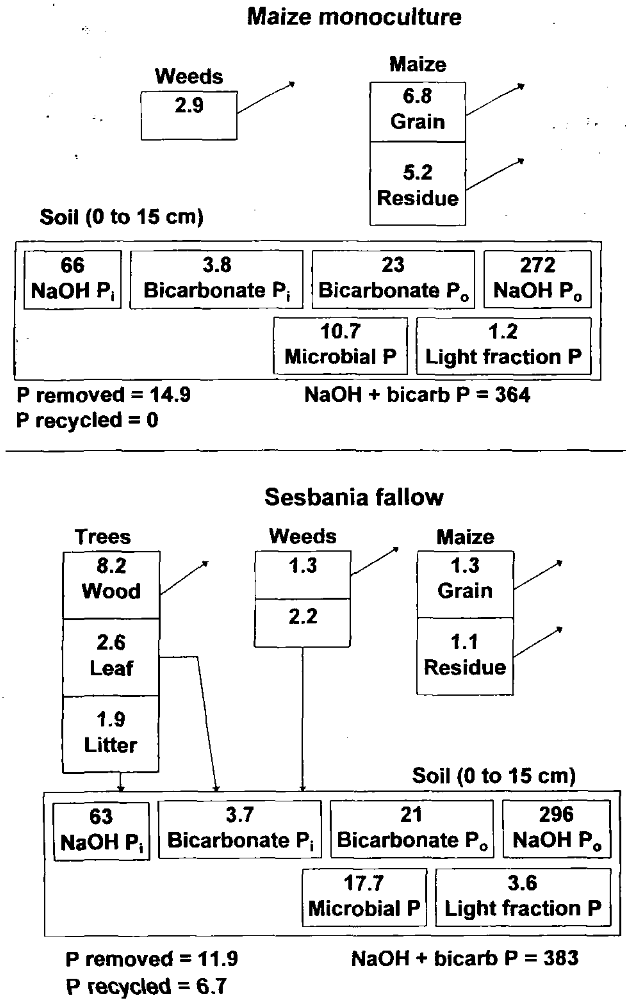

Fig. 6-2. Effect of maize monoculture and a maize-sesbania fallow system on a P-deficient Eutrudox in western Kenya on export and cycling of plant P for 2 yr (4 seasons) and on soil P fractions after 2 yr. All values are in kilograms of P per hectare.

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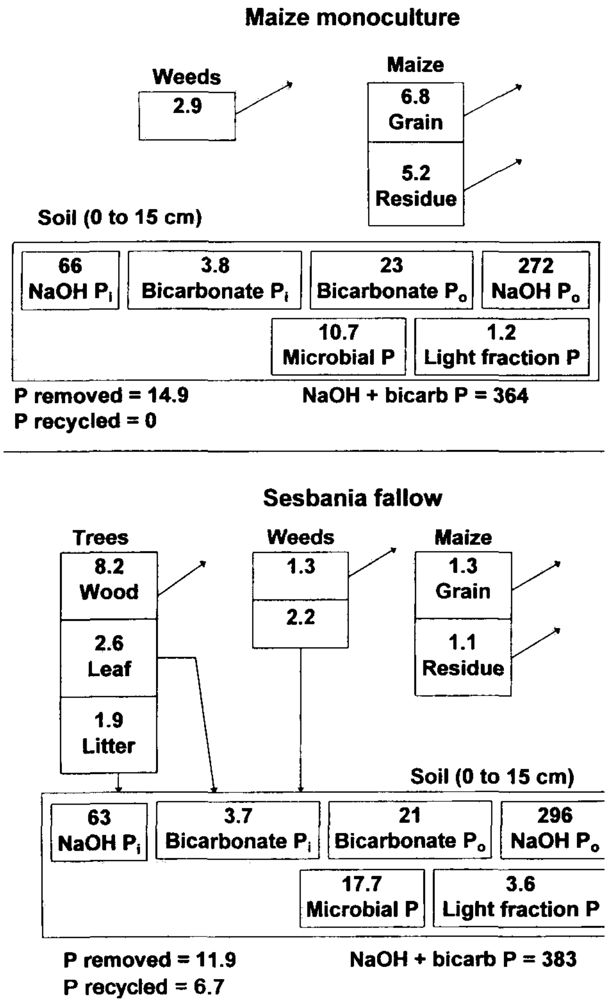

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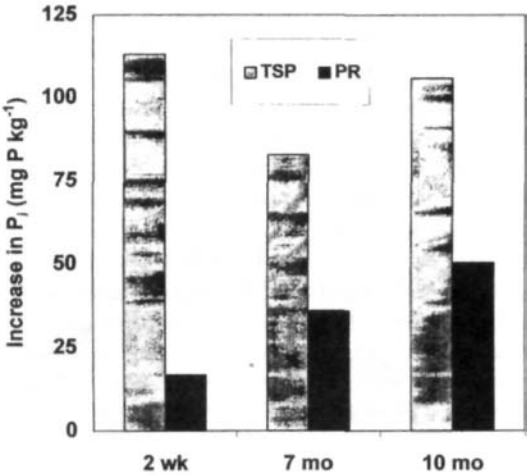

Fig. 6-3. Effect of 250 kg P ha^{-1} as triple superphosphate (TSP) and Minjingu
on increase in bicarbonate plus NaOH P_i in an acid soil in western Kenya (M

The recovery of added TSP-P at 10 mo (Fig. 6-3) was 11% in bicarbonate P_i and 59% in NaOH Pj. The latter is similar to the 52 to 58% recovery of added TSP-P in NaOH *P,* on an Ultisol with 60% clay (Linquist et al., 1997a). On soils with lower P-sorption capacity, the recovery of fertilizer P tends to decrease in the NaOH P_i fraction and increase in more labile fractions (resin and bicarbonate Pj). The NaOH Pj, nonetheless, is a primary sink for fertilizer P even on low P-fixing soils (Aulakh & Pasricha, 1991).

Small applications of soluble P fertilizer to P-deficient soil with low or moderate P-sorption capacity can increase crop yields with little or no detectable build up in extractable soil P_i. Broadcast application of 25 kg TSP-P ha^{-1} and placement of 10 kg TSP-P ha^{-1} in the planting hole, for example, increased maize yield in the two cropping seasons after P application on an Eutrudox with 42% clay in western Kenya (Table 6-1). These low P rates had no detectable effect on liquid P in the bulk soil, as estimated by resin P. A build up of liquid P and capital P, however, may have occurred in the vicinity of fertilizer granules.

A larger application of TSP (>50 kg P ha^{-1}) increased resin P in the bulk soil at the end of the first maize cropping season (5 mo after P application; Table 6-1). Resin P rapidly decreased between the end of the first and second seasons after P application, and the percentage decrease was greater for high (100-250 kg ha^{1}) than moderate (50 kg ha^{-1}) P rates. Other researchers have similarly found greater percentage declines in bicarbonate P_i and double acid extractable P (Cox et al., 1981) and Mehlich-1 extractable P (Linquist et al., 1996) following high than low rates of P application.

Application of PRs classified as medium or highly reactive (Diamond, 1979; Hammond & Leon, 1983) can increase capital P, as determined by NaOH Pj, in acid soils. For PRs, reactivity is indicative of the rate and extent of PR dissolution in soil and is determined by their inherent mineralogy. Application of

Table 6-1. Effect of rate and method of application of triple superphosphate (TSP) on soil resin P, maize grain yield, and added net benefit on an Eutrudox in western Kenya (Palm et al., 1996, unpublished data).

			Resin P		Grain yield		Added nel: benefitt	
Treat-ment	Prate	Application method	End of 1 st season	End of 2nd season	1st season	2nd season	1st season	1st + 2nd season
	kg ha"[1]		——mg:P kg-' —		— tha'" —		— US$ ha-[1]——	
1	0		3	3	2.1	0.8	-107	-225
2	25	Broadcast	4	4	4.4	1.5	219	212
3	50	Broadcast	7	6	4.4	1.7	**148**	173
4	100	Broadcast	17	6	5.6	2.0	216	284
5	150	Broadcast	20	9	5.4	1.4	34	17
6	250	Broadcast	33	16	5.1	1.7	-286	-259
7	10	Seed placed§	4	4	3.9	1.6	242	243
SED1			2.7	2.5	0.85	0.42	143	181

Phosphorus was applied only in the first season.

Urea was applied at 100 kg N ha^{-1} to all plots in the first season. The added net benefits were determined by partial budgeting, in which only costs and benefits that varied from the control with no added P and no added urea (i.e., costs of fertility-enhancing inputs and the value of increased maize yield) were considered. Grain yield for the control was 2.6 t ha^{-1} in the first season and 1.5 t ha^{-1} in the second season. The analysis used costs from Jama et al. (1997).

Phosphorus fertilizer was mixed with soil in the planting hole at the time of planting.

SED, standard error of the difference in means. Error df = 12.

250 kg P ha^{-1} as reactive Minjingu PR increased bicarbonate plus NaOH Pj by 17 mg P kg^{-1} at 2 wk after application on an acid soil in Kenya. The recovery of added P in bicarbonate plus NaOH P_i steadily increased to 50 mg P kg^{-1} at 10 mo (Fig. 6-3). The recovery of added PR-P in NaOH P_i was 8% at 2 wk and 27% at 10 mo.

The P from water-soluble P sources (e.g., TSP) is rapidly released to labile soil P and then to capital P, as determined by NaOH P_t. The P in most PRs is only slowly released in acid soils resulting in a gradual build up of NaOH P_i(Fig. 6-3). Substantial yield increases observed in the year of application of reactive PRs indicate that reactive PRs also increase liquid P and supply P to the crop in the first season (Bationo et al., 1986; Heliums et al., 1992). The NaOH P_i,included in Fig. 6-3, underestimates total capital P following PR application because it does not include undissolved PR, roughly estimated with HCl P, that gradually releases P for a number of seasons.

Soil Phosphorus Requirements

Based on P sorption isotherms for 200 soils from West, East, and southern Africa, Warren (1992) concluded that fertilizer P requirements tend to follow the order Andisols > Oxisols > Ultisols > Alfisols > Entisols. There is much variability in P requirements among soil orders, but for soils other than Andisols there is generally a direct relationship between P requirements and surface area of Fe and Al oxides, which is a function of clay content and mineralogy. Soils derived from volcanic ash (Andisols) characteristically have high P sorption, resulting in low recovery of added P (Sanchez & Uehara, 1980; Vander Zaag & Kagenzi, 1986). Because of the irreversible nature of P sorption in these soils, there is typically little residual effect of P applications. Andisols are important in localized areas in East and Central Africa, but they are relatively unimportant overall in Africa. Some soils near young volcanos, on the other hand, have received volcanic ash. Such soils with volcanic admixtures can be relatively fertile and high in available P (Wielemaker & Boxem, 1982).

Large areas of Africa, particularly in the semiarid tropics, are dominated by sandy soils with low P sorption and hence low fertilizer P requirements (Mokwunye et al., 1986; Warren, 1992). A modest annual application of 15 to 20 kg P ha^{-1} is usually adequate for these soils (Bationo & Mokwunye, 1991). Baidu-Forson and Bationo (1992), in an evaluation of a 6-yr experiment on a Psammentic Paleustalf (94% sand) in Niger, recommended annual application rates of 17.5 kg P ha^{-1} as SSP in combination with N and K fertilizer. When 5 t manure ha^{-1} was applied every third year, the annual P application could be reduced to 8.7 kg P ha^{-1} as SSP.

Warren (1992) found more varied P sorption among soils from East and southern Africa than from West Africa, but many soils in East Africa have medium to high P requirements, based on P sorption isotherms. Phosphorus sorption is not routinely determined in African laboratories or elsewhere, but P-sorption capacity of acid soils can be generally approximated from Fe and Al oxide content, clay content, and red color. Braun et al. (1997), therefore, used relatively easily obtainable information on soil clay content and color to develop indicators of potential P fixation for soils in the highlands of East Africa based on the Fertility Capability Classification (Sanchez et al., 1982). They used the criteria that highly P-fixing soils were Andisols (Andosols in FAO/UNESCO, 1977) and moderately P-fixing soils had > 35% clay and Munsell 5YR or redder. Based on available data for 63% of the highlands (1200-3300 m altitude and > 400 mm rainfall for 5 consecutive months) in Kenya, about 50% of the soils in the highlands were moderately P fixing and 16% were highly P fixing. In Ethiopia, 36% of the highland soils were moderately P fixing and 1% was highly P fixing.

Based on soil nutrient depletion (Smaling et al., 1997, this publication) and P-sorption capacity, the highly weathered soils in the densely populated and intensively cultivated highlands of East Africa typically have higher fertilizer P requirements than the low P-fixing soils in West and southern Africa. In subsequent discussions in this chapter, reference to P-sorption capacity will be based on P sorption isotherms (Fox & Kamprath, 1970) where sorbed P at 0.2 mg solution P L^{-1} is <100 mg P kg-' soil for low P-fixing soil, 100 to 400 mg P kg^{-1} soil for moderate P-fixing soil, and >400 mg P kg^{-1} soil for high P-fixing soil. Some soils referred to as P fixing by Sanchez et al. (1997, this publication; see Fig. 1-3) are moderate P fixing by our definition.

Relatively small rates of P fertilizer (10-25 kg P ha^{-1}), particularly when mixed with soil in the planting hole, can increase crop yield and be financially attractive on moderate P-fixing soils in the highlands of East Africa (Table 6-1; Jama et al., 1997). Crop yields can be further increased with higher P rates, which can also be financially attractive (e.g., 100 kg P ha^{-1}, Table 6-1). Measurements of crop response and financial benefits for P fertilizer in farmers' fields can be highly variable, as illustrated by the large standard error of the difference in means (SED) in Table 6-1. The variability arises from heterogeneity not only in soil fertility but also in other crop-limiting factors, such as diseases and pests (e.g., incidence of *Striga* sp.).

EXTERNAL SOURCES OF PHOSPHORUS CAPITAL

The sources of P that can be provided in sufficient quantities for building soil P capital are essentially limited to soluble P fertilizers and some PRs that are capable of supplying P on acid soils within a reasonable time frame of 10 yr. As indicated previously, organic materials are typically too low in P content and too limited in supply to represent a substantial source of P for building soil P capital. Organic materials are more suited as supplements with inorganic P sources (see Palm et al., 1997, this publication).

Indigenous Phosphorus Sources

In some cases the direct application of indigenous PR as a source of capital P is viewed as an attractive option for building soil P fertility because it potentially involves lower production costs and capital investments than the production of water-soluble P fertilizers from indigenous PR sources (Hammond et al., 1986b; Rajan et al., 1996). Phosphate rock deposits are scattered throughout Africa (Fig. 6—4). Deposits in West Africa are predominantly sedimentary, whereas those in East Africa are predominantly of igneous origin. Exceptions in East Africa include Minjingu PR a sedimentary deposit in Tanzania, and lies Barren PR a relatively small guano deposit in Madagascar.

Generally speaking, sedimentary ores are more soluble and tend to be less costly to excavate and process than igneous ores. Some agromineral resource evaluations and site-specific phosphate deposit studies have been conducted in Africa (Savage, 1987; Van Kauwenbergh, 1991), but verified details on the size and composition for many of the deposits are fragmented (Table 6-2). In such cases, the limited availability of geologic information has prevented an economic analysis on the use of the PRs. There is a need to update the information on PRs presented in Fig. 6-4 and Table 6-2.

Phosphate rocks with low reactivity (Table 6-2) will require additional processing of the PR raw material before the material can be used in improving soil P capital within a reasonable time frame of 10 yr. Partial acidulation of PR is an alternative use for indigenous PR that is too low in reactivity for direct application (Bolan et al., 1990; Rajan & Marwaha, 1993). The production of partially acidulated PR (PAPR) uses only a portion of the acid required for production of SSP and hence has a lower cost than SSP (Schultz, 1986). PAPR has been shown to be effective on sandy soils with low P sorption in West Africa (Chien & Menon, 1995a). The water-soluble P from PAPR presumably promotes early root growth following application of PAPR thereby enabling more effective use of P from PR (Hammond et al., 1986b). The factory-gate cost of P from sulfuric acid-based 50% PAPR is about 80% of the cost of P from SSP (Schultz, 1986). Phosphorus content is lower for PAPR than for high-analysis fertilizers such as

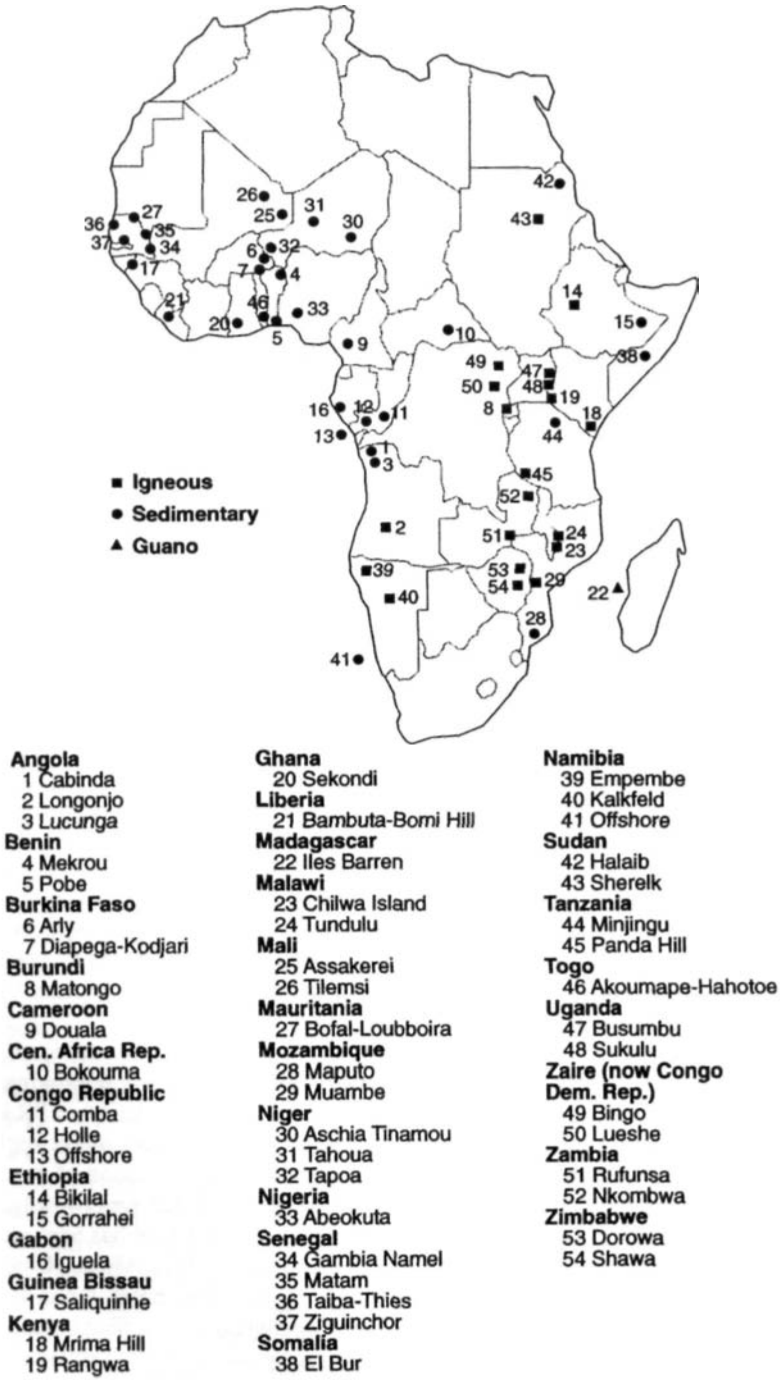

Fig. 6-4. Phosphate rock deposits in sub-Saharan Africa (adapted from McClellan & Notholt, 1986; P. van Straaten, 1997, personal communication).

Table 6-2. Estimated resources of some phosphate rocks (PR) in sub-Saharan Africa.

Country	Name of deposit	Type of PR	Reactivity	Estimated reserves of PR	Total P content	1994 production
				10^6 tonnes	g P kg^{-1}	10^6 tonnes PR
Angola	Cabinda and Lucunga	Sedimentary	Medium	28	109	
Burkina Faso	Kodjari	Sedimentary	Low to medium	63	109-140	
Burundi	Matongo	Igneous	Low	25	48	
Congo D.R.	Lueshe	Igneous	NA#	30	17-44	
Guinea Bissau	Saliquinhe	Sedimentary	NA	112	131	
Madagascar	lies Barren	Guano	Medium to high	0.61	122-166	
Mali	Tilemsi	Sedimentary	Medium	20-25	66-140	
Mauritania	Bofal-Loubboira	Sedimentary	NA	94	83-87	
Niger	Tahoua and Pare W	Sedimentary	Low to medium	100	79-153	
Senegal	Taiba and Thies	Sedimentary	Medium to high	155	122-166	1.59
South Africa	Phaloborwa	Igneous	Low	1800	26	2.55
Tanzania	Minjingu	Sedimentary	Medium to high	10	87-109	0.10
Tanzania	Panda Hill	Igneous	Low	125	26	
Togo	Hahotoe	Sedimentary	Low	100	122-140	2.15
Uganda	Sukulu Hill	Igneous	Low	230	48-57	
Zambia	Nkombwa-Rufunsa	Igneous	Low	700	17	
Zimbabwe	Dorowa	Igneous	Low	471	35	0.15

† Sources, McClellan and Notholt (1986), Sheldon (1987), and Van Kauwenbergh (1995) unless indicated otherwise.

‡ Reactivity of a PR is determined by its inherent mineralogy and is correlated to the amount of citrate soluble (CS) P in the PR: High reactivity >25 g CS P kg^{-1}, medium reactivity = 15 to 25 g CS P kg^{-1}, and low reactivity <15 g CS P kg^{-1}.

§ From FAO (1996), except for Minjingu PR.

¶ From IFDC/CIRAD/ICRAF/NORAGRIC (1996).

NA, not available.

†† Extraction in 1995. Production halted in 1996-1997 because of excess stock and closure of Tanga fertilizer factory (E.P. Mwaluko, Mipco Ltd, Nairobi, 1997, personal communication).

TSP, diammonium phosphate (DAP), and monoammonium phosphate (MAP). Therefore, transport cost will be relatively higher for PAPR, and adversely affect its economic attractiveness.

Partial acidulation is not suitable for PRs with high Fe and Al oxide contents. The Fe and Al oxides react with water-soluble P formed during the acidulation of PR to form water-insoluble forms of P (Hammond et al., 1989; Chien & Menon, 1995a). The removal of Fe and Al oxides from raw PR ore by beneficiation can result in a high-grade ore suitable for partial acidulation (Butegwa et al., 1996a), but this substantially increases the cost (IFDC, 1990, unpublished data).

An alternative to partial acidulation of low-reactive PR is compaction of the PR with water-soluble P fertilizer, such as TSP (Lupin & Le, 1983; Menon & Chien, 1996). Compaction with soluble P fertilizer and partial acidulation are equally effective for low-reactive PR with low Fe and Al oxides; but compaction with soluble P is more effective than partial acidulation for PR that is high in Fe and Al oxides (Menon & Chien, 1990; Menon et al., 1991, 1995). The relative effectiveness of PAPR and compacted PR plus soluble P fertilizer, with respect to soluble P fertilizer alone, has been reported to be greater on soils with high than low P-sorption capacity (Mokwunye & Chien, 1980; Chien & Hammond, 1989). Butegwa et al. (1996b), however, recently reported that PAPR and compacted PR plus TSP prepared with unreactive Sukulu Hills PR from Uganda did not increase in relative effectiveness with increasing soil P-sorption capacity on soil limed to pH6.0.

The physical combination of water-soluble P with PR, as in PAPR and compacted PR plus soluble P fertilizer, can result in chemical interactions that increase the effectiveness of P use from PR by crops (Mokwunye & Chien, 1980). When both water-soluble and water-insoluble P are present, some acid produced from dissolution of the soluble P source is neutralized by the PR and hence does not react with Fe and Al minerals in the soil to form insoluble Fe-Al phosphates. The reaction of acid with PR might also release additional P into solution (Mokwunye & Chien, 1980; Chien & Menon, 1995a). Recent results from a pot study by Chien et al. (1996) indicate that soluble P fertilizer can enhance the effectiveness of PR even when the soluble P and PR are not physically combined. Phosphorus uptake from PR by maize and cowpea *[Vigna unguiculata* (L.) Walp. sp. *unguiculata]* in a greenhouse study was increased by a physically separate application of TSP. The water-soluble P from TSP presumably enhanced early root development, which enabled more effective utilization of P from PR than when PR was applied alone. These pot study results require examination and verification under field conditions.

Commercial Phosphorus Sources

Phosphorus fertilizer consumption in Africa is relatively low on an area basis and largely concentrated in a few countries. Total P fertilizer consumption in 1994—1995 in sub-Saharan Africa, excluding South Africa, was 0.17 x 10^6 tonnes P (FAO, 1996). This represents only 38% of the total P consumption in continental Africa, and it is only marginally greater than the P consumption in South Africa alone (0.13 x 10^6 tonnes P). Nigeria, Kenya, Zimbabwe, and

Ethiopia accounted for 66% of the P consumption in 1994-1995 in sub-Saharan Africa, excluding South Africa.

Phosphorus imports in 1994-1995 in sub-Saharan Africa, excluding South Africa, (0.17 x 10^6 tonnes P) were comparable to P fertilizer consumption. Some of the imported P, particularly in Nigeria, was used in manufacturing fertilizers (Gerner & Harris, 1993). The most important sources of P fertilizer in Africa are SSP, TSP, ammonium phosphates, and other compound fertilizers. These soluble P fertilizers are normally comparable in agronomic effectiveness per unit of P. High-analysis fertilizers, however, are favored because of their relatively lower transportation cost per unit of P, although SSP can be a desirable fertilizer when sulfur is required.

Even though PR deposits are found throughout sub-Saharan Africa, only those in Senegal, South Africa, Togo, and Zimbabwe have been developed on a large commercial scale (Table 6-2). In Togo, the PR is exported. In Senegal and South Africa, the PR is both exported and used in the domestic manufacture of fertilizers. In Zimbabwe, the PR is used solely for the domestic manufacture of SSP and TSP. The SSP is marketed directly, whereas the TSP is either used in compound fertilizers or mixed with SSP to form double superphosphate (Johnsen et al., 1996).

MANAGEMENT OF PHOSPHORUS INPUTS

Targeting Inorganic Phosphorus Sources

The suitability of a PR for direct application to soil depends upon the mineralogy and reactivity of the PR, soil properties, the crop, and the economics of use associated with the PR. Only PRs with high or medium reactivity are potentially suitable for direct application. The PR must be incorporated into the soil; and except in the case of highly reactive PRs, the PR must be finely ground. High soil solution Ca slows down the dissolution of PR because Ca ions are released during PR dissolution (Robinson & Syers, 1990). The effective dissolution of PR in soil requires low soil pH, low soil exchangeable Ca, and low soil solution P concentration (Khasawneh & Doll, 1978; Chien & Menon, 1995b; Rajan et al., 1996). Direct application of PR is normally not recommended for low rainfall areas, due to erratic agronomic effectiveness under conditions of low soil water content (Hammond et al., 1986b).

The dissolution of PR increases as soil P-sorption capacity increases (Smyth & Sanchez, 1982; Mackay et al., 1996), but extractable P also decreases with increasing soil P-sorption capacity (Syers & Mackay, 1986; Kanabo & Gilkes, 1987). The short-term agronomic effectiveness of both PR and soluble P fertilizer decreases with increasing P-sorption capacity due to decreasing soil solution P (Mokwunye & Chien, 1980). The determination of relative effectiveness of PR and soluble P fertilizer on soils with varying P sorption, however, has been confounded by differences in other soil properties, such as pH and exchangeable Ca (Chien et al., 1980; Hammond et al. 1986b). Hammond et al. (1986a), in a greenhouse experiment, altered the P sorption of a soil through the addition of amorphous Fe gel while holding other soil properties constant. They found that the effectiveness of PR relative to TSP decreased with increasing P-sorption capacity. Although a high P-sorption capacity can promote more rapid dissolution of PR, the low soil solution P concentration resulting from high P sorption may limit plant growth (Mokwunye & Hammond, 1992).

The effectiveness of plant use of P from PR varies among cultivars (Ankomah et al., 1995) and species (Flach et al., 1987; Bekele & Hefner, 1993). Plants can enhance the dissolution of PR through acidification of the rhizosphere (Hinsinger & Gilkes, 1996), high uptake of Ca (Hinsinger & Gilkes, 1997), secretion of organic acids that complex Ca (Hoffland, 1992), and depletion of P in soil solution (Rajan et al., 1996). The relative effectiveness of PR compared with soluble P fertilizers also is generally greater for long-duration crops and perennials man for short-duration crops (Pushparajah et al., 1990; Sale & Mokwunye, 1993).

A few PR deposits, such as the Tilemsi in Mali (Henao & Baanante, 1997), Tahoua in Niger (Bationo & Mokwunye, 1991), and Minjingu in Tanzania (Anderson, 1970; IFDC, 1990), are sufficiently reactive for direct application. Many other deposits, such as Pare W in Niger (Bationo et al., 1990), Hahotoe in Togo (Kpomblekou et al., 1991), and Sukulu Hills in Uganda (Butegwa et al., 1996a) are not sufficiently reactive for direct application. As indicated previously, in order for low-reactive PRs to be used as a P source, additional processing is required; however, additional processing (e.g., partial acidulation or compaction) increases cost significantly and results in a product where the soluble P content as a percentage of total P remains considerably lower than for high-analysis, soluble P fertilizers.

Application Strategies

The agronomic effectiveness of PR is frequently determined from the comparison of PR and a soluble P fertilizer at relatively large, one-time applications. Large applications of soluble P can have long-term residual effects on crop yield (Kamprath, 1967; Sanchez & Salinas, 1981), liquid P, and capital P (Linquist et al., 1997a). Crop yields (Janssen et al., 1987; Wolf et al., 1987) and extractable P (Linquist et al., 1996), nonetheless, eventually decline following large applications of soluble P, and the one-time application of PR may have a longer term residual value than an equivalent one-time application of soluble P fertilizer (Rajan et al., 1996).

Predicted crop yield, relative to yield when P is not limiting, for about a 10-yr time frame is illustrated conceptually in Fig. 6-5a for one-time applications of soluble P fertilizer and contrasting PRs. Relative yield will be somewhat less for high-reactive PR than for soluble P in the years immediately following application, but yield may eventually be comparable and slightly greater with the reactive PR. Relative yield will be considerably less for low-reactive PR than for soluble P following application, but with time yield may be greater with PR; however, cumulative yield would be considerably less for the low-reactive PR than for soluble P. The relationships illustrated in Fig. 6-5a will depend upon soil properties, cropping system, and climatic factors (Rajan et al., 1996). The residual benefit from P fertilizers, for example, would increase with increasing P sorption. Therefore, the anticipated decline in relative yield following one-time P applications would be less rapid as P-sorption capacity increases.

A study in Niger confirmed that medium-reactive PR can be nearly as effective as soluble P fertilizer in the seasons immediately following application, whereas low-reactive PR was much inferior to soluble P fertilizer. The relative agronomic effectiveness (RAE), defined as (yield increase with PR/yield increase with soluble P) x 100, following a one-time application of medium-reactive Tahoua PR and SSP ranged from 82% in Year 1 to 104% in Year 3 with pearl millet *[Pennisetum glaucum* (L.) R. Br.]. The RAE for low-reactive Pare W PR was 47% in Year 1 and 31% in Year 3 (Bationo & Mokwunye, 1991). These results indicate that medium- to high-reactive PRs rapidly contribute P to both liquid P and capital P, as shown for Minjingu PR in Fig. 6-3.

Bromfield et al. (1981), in a comparison of a one-time application of medium- to high-reactive Minjingu PR and SSP to maize on an acid soil in western Kenya, reported a RAE for PR of only 26% in the first season. When examined over five successive seasons, however, the cumulative RAE for PR was 75%. The low RAE of Minjingu PR reported after one season (26%) by Bromfield et al. (1981), however, may be a result of band rather than broadcast application of the PR. Banding of PR is frequently less effective than broadcasting and incorporating PR (Chien & Menon, 1995b).

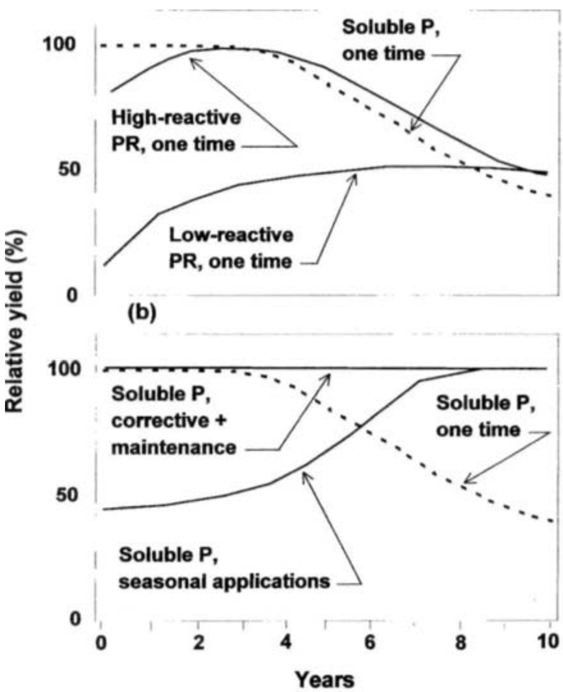

Fig. 6-5. Effect of soluble P fertilizer and phosphate rock (PR) on predicted crop yield, relative to yield when P is not limiting, following equal rates of P application on moderate P-fixing soil [Part (a) adapted from Rajan et al., I996).

Seasonal applications of soluble P fertilizers might be more attractive than one-time applications for building capital P on low to moderate P-fixing soil (Bationo & Mokwunye, 1991). Seasonal applications of relatively small amounts of soluble P would enable the use of P on a larger land area at rates on the steeper part of the P response curve. Predicted crop yield from seasonal application of soluble P fertilizer, relative to yield when P is not limiting, will remain constant or gradually increase with time (Fig. 6-5b), depending on the rate of P application. Cumulative yield could eventually be greater for seasonal than for a one-time application of soluble P fertilizer. On high P-fixing soils, however, relatively small applications of soluble P can be ineffective in increasing yield (Sanchez & Salinas, 1981).

Crop yield with low- to medium-reactive PR could be increased in the seasons immediately following PR application by initial application of soluble P fertilizer (Fig. 6-6a). Crop yield with medium- to high-reactive PR could be increased by application of soluble P in later seasons when the residual effect of the PR is declining (Fig. 6-6b). The combined use of PR and soluble P fertilizers merits agronomic and economic assessment.

In conceptual terms, a one-time application of soluble P dramatically increases capital P, and then the capital P gradually decreases as P is increasingly sorbed and converted to inert P (Fig. 6-7). A one-time application of a suffi-

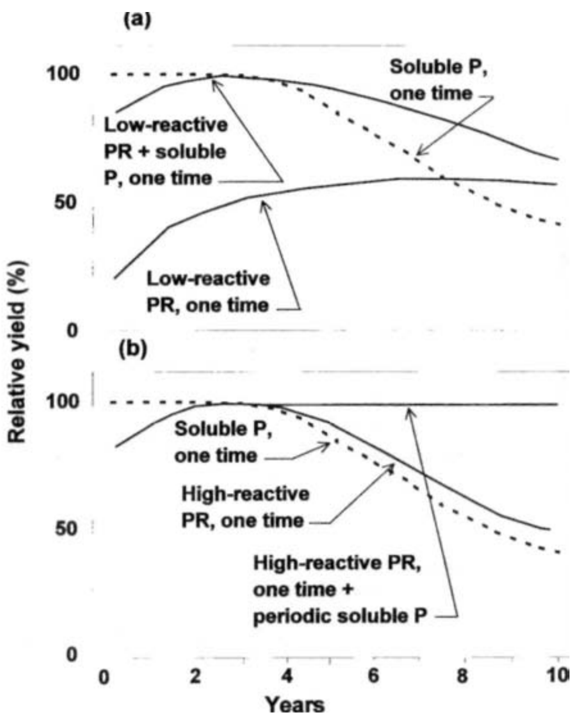

Fig. 6-6. Effect of adding soluble P fertilizer with phosphate rock (PR) on predicted crop yield, relative to yield when P is not limiting, on moderate P-fixing soil.

ciently reactive PR can dramatically increase capital P, which includes PR that releases P to liquid P pools for up to 10 yr. The maximum level of capital P will be lower following application of PR than of soluble P, but PR might have longer lasting effects on capital P. Applications of PR, particularly sedimentary PRs of low reactivity or igneous PRs, would contribute primarily to *inert P* that does not become available to plants within 10 yr and hence is not capital P. The relationships illustrated in Fig. 6-7 will depend upon reactivity of the PR, soil properties, and the cropping system.

The residual effect of soluble P fertilizer on building soil P capital may eventually be greater with seasonal applications than a single large, one-time application (Fig. 6-7; Cox et al., 1981; McCollum, 1991; Linquist et al., 1996). The decline in extractable P_i with time after application of soluble P fertilizer is generally a first-order chemical reaction (McCollum, 1991). The decline is particularly rapid when extractable soil P_i is high (Cox et al., 1981; Linquist et al., 1996), as is the case after large P applications. Cox et al. (1981) found for soils with contrasting P-sorption capacity that seasonal P applications gave either an increase or a more gradual decrease in extractable P_i than a one-time P application. Hence, the seasonal application of soluble P at rates exceeding P uptake by plants can gradually build up liquid P and capital P to higher levels than a one-time application of P (Fig. 6-7). The gradual build up of capital P from seasonal applications rather than an immediate build up with a large P application, however, can result in considerably less crop yield for several seasons on moderate and high P-fixing soils (Fig. 6-5b).

Because of the decline in liquid P and capital P after P application, a large application of P to rapidly rebuild soil P capital must be followed within a few years by periodic *maintenance* applications of P in order to maintain capital P. This strategy of a one-time *corrective* P application to reestablish soil fertility levels for high productivity followed by periodic maintenance applications of P, as

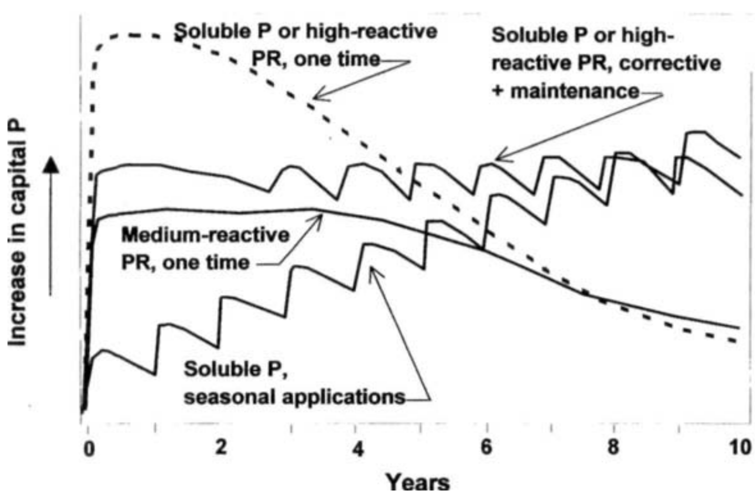

Fig. 6-7. Conceptual diagram of changes in capital P following application of phosphate rock (PR) and soluble P fertilizer. Total rates of added P are comparable in each case.

described by Pieri (1987) and Sanchez et al. (1997, this publication) for Africa and successfully used in the Cerrado of Brazil (Goedert, 1987; Lopes & Guilherme, 1994), will build and maintain soil P capital (Fig. 6-7). It can immediately eliminate P deficiency and then maintain soil P above deficiency levels, thereby resulting in higher cumulative crop yields than with either a sole, one-time application of P or seasonal P applications (Fig. 6-5b). The first maintenance application of P can be delayed until several seasons after the corrective P application without loss of crop yield. The length of this delay will increase with increasing rate of the corrective P application and increasing P-sorption capacity of the soil.

One-time applications of PR should be compared in agronomic studies with seasonal applications of soluble P and corrective plus maintenance applications of soluble P rather than with only one-time applications of soluble P. Seasonal or periodic applications of medium- and high-reactive PR also merit investigation. Application of PR for several years can result in accumulation of undissolved PR in soil. The subsequent release of P from this undissolved PR could result in appreciable residual value (Rajan et al., 1996). Undissolved PR represents capital P if it supplies liquid P (a service flow) within 10 yr.

Application of Soluble Phosphorus Sources

Agronomic studies in Africa indicate occasional but not consistent superiority of spot or band placement compared with broadcast and incorporation of soluble P fertilizers (Warren, 1992). Experiences from the Brazilian Cerrado led to the recommendation of initial broadcast and incorporation of soluble P followed by annual band applications of soluble P on soils with high P-sorption capacity and very low available P (Sanchez & Salinas, 1981). Broadcast application was superior to band application in the season after P application (Yost et al., 1979). Band application, however, leads to gradual yield increases and greater residual effect than broadcast applications (Yost et al., 1981).

Band or localized placement of soluble P can be effective on P-deficient soils with moderate or low P-sorption capacity (Holford, 1989). Fox and Kang (1978) found for maize on a sandy loam Alfisol that band application was superior to uniform incorporation of TSP at only suboptimal P rates.

The application of small and moderate quantities of soluble P fertilizer (10 to 30 kg P ha^{-1}) to maize by either mixing in the planting hole or by broadcast and incorporation can be economically attractive on moderate P-fixing, P-deficient soil (Jama et al., 1997; Table 6-1). In the results from western Kenya (Table 6-1), added net benefits were negative for application of N without P (Treatment 1) because the application of 100 kg urea-N ha^{-1} without P did not increase yield in the first season and slightly decreased yield in the second season. Applications of TSP with urea up to 100 kg P ha^{-1} increased yield and provided positive net benefits.

Economic Factors

In conceptual terms, PR will be more attractive than a high-analysis, soluble P fertilizer when RAE is greater than the relative cost of PR, defined as (farm gate + application costs per kilogram P from PR)/(farm gate + application costs per kilogram P from soluble P fertilizer) x 100. Even though unreactive PRs can have a low relative cost compared with soluble P fertilizer, they are agronomically and economically unattractive for direct application because of their very low RAE (Fig. 6-8). Sukulu Hills PR, for example, is a large deposit in eastern Uganda near P-deficient soils in western Kenya, but it has a very low RAE as reflected by its failure to increase maize yields in a pot study (Butegwa et al., 1996a). Sukulu Hills PR would require processing, such as beneficiation and compaction with soluble P, before being used.

Processing of unreactive PR, such as Sukulu Hills, would dramatically increase its RAE (Butegwa et al., 1996a), but the cost of the processed PR relative to high-analysis, soluble P fertilizer also would increase. The processed PR must have a higher RAE than relative cost to be more economically attractive than high-analysis P fertilizer (Fig. 6-8). Phosphate rock processed by partial acidulation or compaction with soluble P fertilizer has a lower total P content, and hence higher transportation cost, than high-analysis P fertilizer. Therefore, processed PR, when compared with high-analysis P fertilizers, will be relatively most attractive in agricultural areas near to the processing facility (Hammond et al., 1986b; McClellan & Notholt, 1986; Henao & Baanante, 1997).

Economic analyses have indicated that many PRs are not economically attractive for direct application (Seyoum & Mclntire, 1987). Minjingu PR is the only known PR deposit in eastern and southern Africa with sufficient quantity and reactivity (Table 6-2) for potential in large-scale direct application. The deposit is located relatively near western Kenya, where many soils are deficient in plant-available P (Kenya Agricultural Research Institute, 1994; Jama et al., 1997). Minjingu PR is currently not marketed in western Kenya, but an estimated retail price of Minjingu PR in western Kenya in December 1996 ranged within US$ 1.3 to 1.8 kg^{-1} P (F. Place, ICRAF, 1997, personal communication). The

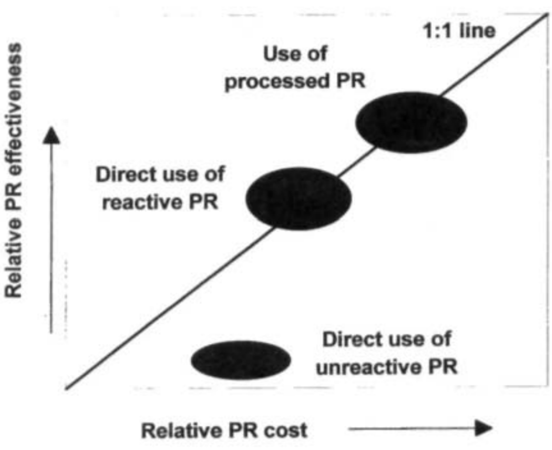

Fig. 6-8. Conceptual diagram of relative agronomic effectiveness and relative cost for phosphate rock (PR) compared with a soluble P fertilizer. Processed PR refers to partially acidulated PR and PR compacted with soluble P.

retail price of TSP in western Kenya in December 1996 was about US$ 2.36 kg^{-1} P. The estimated cost of Minjingu PR on a P basis in western Kenya might therefore be about 55 to 76% of the cost of TSP. This value must be interpreted with caution. The retail price of Minjingu PR, estimated from acquiring moderate amounts of PR for research and a pilot project, could change if the PR were mined and delivered to western Kenya on a large scale.

Labor costs will be slightly higher for application of PR than TSP. PR has a lower total P content than TSP, and the fine particle size of ground PR can result in considerable dust during handling and application on farms. This dust can lead to dislike of the ground PR by farmers and to higher labor requirements for application of ground PR as compared with granular, high-analysis P fertilizer (Ballo, 1995).

Currently available data indicate that the estimated 55 to 76% relative cost of Minjingu PR compared with TSP compares favorably with the approximately 75% RAE of Minjingu PR on acid soils in western Kenya. Bromfield et al. (1981) reported a RAE of 75% for Minjingu PR in the five seasons following application to maize in western Kenya. In a recent study with maize on an acid, P-deficient soil in western Kenya, the RAE in the first season after P application averaged 74% at 50 kg P ha^{-1} and 80% at 250 kg P ha^{-1} (ICRAF, 1997). Under such conditions of comparable RAE and relative costs, there might be an economic incentive for using Minjingu PR in western Kenya.

Phosphate rocks can contain radionuclides (uranium, radium, and thorium) as minor constituents. The concentration of the radionuclides, which depends on the origin of the PR, is relatively high in Minjingu PR. This can present an occupational hazard to workers at the Minjingu mine (Mustonen & Annanmaki, 1988). Application of P fertilizers at recommended rates has been shown to not increase the level of radionuclides in the human food chain. Mortvedt and Beaton (1995), for example, reported that annual applications of about 30 kg P ha^{-1} for >50 yr as fertilizer made from Florida PR, which contains radionuclides, had no effect on radionuclide concentration in tissues of field crops. The effect of large applications of PR, relatively high in radionuclides, on subsequent radionuclide concentration in soil components and harvested plant products nonetheless merits investigation.

In West Africa, the underutilized medium-reactive Tilemsi PR offers the most promise as an indigenous PR source for direct application. Results from a 5-yr study in four agroecological zones in Mali showed that Tilemsi PR was a suitable source of P for sustainable production of important cropping systems. Tilemsi PR produced 85 to 90% of the yields obtained with an equal application of P from TSP (Henao & Baanante, 1997). Economic feasibility and profitability analyses indicated that the use of Tilemsi PR was financially attractive to farmers under the prevailing crop prices and climatic conditions. Cost-benefit analyses indicated that a decrease in PR production from a projected 10 000 t yr^{-1} would substantially increase costs. Poor rainfall and/or a sudden decline in prices for crop outputs could make the investment in P unprofitable for farmers, regardless of the P source (Henao & Baanante, 1997).

In Africa, only a few PRs are presently both agronomically and economically attractive to use. Phosphate rocks that are sufficiently reactive for direct application often have constraints adversely affecting the economics of use. These potential constraints include deposit size, production limitations (e.g., source of energy to support mining and grinding operations), lack of infrastructure, and in some cases the presence of undesirable constituents (e.g., Cd or radionuclides).

For the less reactive or unreactive PRs, research on increasing solubility by partial acidulation and by compaction with soluble P has provided promising agronomic results; however, when all costs (processing, distribution, and marketing) and benefits (increased yields) are considered, it is probable that partial acidulation of indigenous PRs will not be the most cost-effective option in large regions of Africa. As of 1996, there was no commercial production of PAPR in Africa.

Research has shown that the availability of P from PR can be enhanced by composting PR with organic materials (Ikerra et al., 1994; Van den Berghe, 1996) and by combination with pyrite, which produces acidity during oxidation (Lowell & Weil, 1995). While these small-scale technologies may appear agronomically promising, particularly for PR with insufficient reactivity for direct application, little is known about their financial attractiveness to farmers.

OPTIONS FOR PHOSPHORUS REPLENISHMENT

Soil P deficiency can be corrected either rapidly with investment in a large, one-time P application or gradually with seasonal P applications at rates sufficient to increase availability of soil P. Both approaches will build up capital P.

One-Time Investment

A rapid, one-time build up can be achieved with a large application of either reactive PR (Fig. 6-5a), soluble P fertilizer (Fig. 6-5a), or low- to medium-reactive PR combined with soluble P fertilizer (Fig. 6-6a). The P rate required to overcome P deficiency will increase with increasing P-sorption capacity of the soil, just as the residual benefit of the one-time application will be longer as P-sorption capacity increases, except for soils with allophane.

A one-time P application, when integrated with appropriate management to overcome other nutrient and crop growth constraints, would ensure a rapid increase in crop yields and rapid soil rehabilitation. The increased soil fertility could provide an incentive for adoption of higher yielding crop varieties and diversification of enterprises within land holdings. This could lead to enhanced farm income, which in turn could increase farmer demand for fertilizers to maintain soil fertility.

Increased crop growth would increase root growth, thereby leading to extraction of nutrients and water from a greater soil volume and to increased cycling of C in the soil. Increased plant growth could also increase ground cover, which could lead to reduced leaching and soil erosion. Application of 500 kg TSP-P ha^{-1}, for example, to a maize monoculture on an Eutrudox with about 3% slope in western Kenya reduced total P loss by erosion and runoff during the 12 mo following P application (M.R. Rao et al., 1997, unpublished data). The reduced P loss was attributed to increased ground cover from weeds and crops during the early growth stages of the crop.

A large, one-time, corrective application of P followed by periodic maintenance applications of P was an essential component in the successful conversion of acid, infertile soils of the Brazilian Cerrado into highly productive soils (Abelson & Rowe, 1987). The Cerrado soils were initially high in Al saturation, low in exchangeable bases, moderate to high in P-sorption capacity, and very low in extractable P (Goedert, 1983). The build up of soil fertility in the Cerrado was achieved with large applications of P combined with application of lime or gypsum, balanced fertilization, improved crop varieties and agronomic practices, and an enabling policy environment (Goedert, 1987; Lopes & Guilherme, 1994). Soil P capital was built up with relatively large applications of soluble P fertilizers and thermophosphates followed by annual maintenance applications of P fertilizers.

Large, one-time applications of P are proposed as an essential component of management for the rehabilitation of degraded acid soils in the humid tropics (Dowdle & Von Uexkull, 1988; Von Uexkull & Mutert, 1995). Deforestation of acid soils has led to degradation of areas in the humid tropics to anthropic savanna. Anthropic savannas covered by imperata *[Imperata cylindrica* (L.) Rausch.] occupy vast areas in Southeast Asia. As a result of limited nutrient cycling and burning, the soils in anthropic savannas are typically low in exchangeable bases, high in Al saturation, and low in extractable P. They can be rehabilitated with a management package including (i) a large, one-time application of reactive PR (1 t ha^{-1}) or TSP plus lime (200 kg P ha^{-1} and 11 Ca ha^{-1}) to correct P and Ca deficiency and (ii) growth of a leguminous creeper *(Mucuna* sp.). The legume suppresses regeneration of imperata, provides rapid ground cover, fixes N_2, improves water retention, stimulates biological activity, and transforms P_i to P_0. The large application of reactive PR or TSP plus lime ameliorates soil acidity, reduces sorption of added P, and increases soil capital P.

The investment in a one-time P application appears most attractive on highly P-deficient soils with high P-sorption capacity (Roche et al., 1980). In such cases, small applications of P would not markedly increase crop growth in the short term. These soils are normally medium to fine textured and frequently high in Al saturation. For soils high in Al saturation, the application of P must be accompanied by application of Ca, which could require the use of soluble P fertilizers because dissolution of PR is significantly reduced in the presence of Ca.

A large, one-time application of P must be viewed as a long-term investment because of the long-term residual benefits from the added P. The justification for the investment would be favored by secure land tenure, rapidly escalating costs for P inputs, and a low opportunity cost for capital. Moreover, a one-time investment that immediately rehabilitates degraded land may in the long term be less costly than waiting to reclaim the land after it has been further degraded. Large corrective P applications may have particularly large impact when targeted to environmentally critical areas (e.g., highly P-deficient soils in erosive parts of a watershed). An immediate rather than gradual rehabilitation of such areas might provide dramatic environmental benefits (e.g., reduced erosion from increased ground cover).

Gradual Build Up of Soil Phosphorus

On many P-deficient soils in Africa, relatively moderate applications of 10 to 20 kg P ha^{-1} can dramatically increase crop yields. Such soils normally have low to moderate P-sorption capacity and no major constraint from Al saturation. Gradual replenishment of these soils could be achieved with seasonal P applications at sufficiently high rates to increase the availability of soil P (Fig. 6-5b, 6-7).

Seasonal applications of P for gradual correction of P deficiency on soils with low to moderate P-sorption capacity will eventually result in greater build up of capital P (Fig. 6-7) and greater crop yields (Fig. 6-5b) than a large, one-time application of P. Gradual build up of soil P capital, however, will provide less immediate and cumulative crop yields than a relatively large corrective P application with subsequent maintenance applications of P on moderate and high P-fixing soils (Fig. 6-5b). Seasonal applications will have increased costs (e.g., transportation, labor for fertilizer handling and application) compared with either one-time applications or corrective plus maintenance applications.

Gradual replenishment with seasonal P applications would, however, enable distribution of a given quantity of P fertilizer to a relatively large land area. Replenishment with a large, one-time P application, on the other hand, would restrict distribution of the P fertilizer to only a portion of the given land area. The remaining land area must wait until subsequent seasons for P application. Gradual replenishment with immediate use of the limited supply of P fertilizer over the entire land area at rates on the steep part of the response curve would result in greater aggregate crop yield for the area. Gradual replenishment also may provide aggregate environmental benefits (e.g., reduced soil erosion) and economic benefits (e.g., increased income) for the area.

Existing knowledge on immediate and residual effects of P fertilizer (Jama et al., 1997; Table 6-1) suggests that the gradual build up of soil P with seasonal applications of P can economically increase crop yields on soils with large crop responses to relatively moderate P rates (10-20 kg P ha^{-1}). Despite knowledge of soil fertility depletion and the need for P fertilizers, many smallholder farmers in Africa have not adopted seasonal application of sufficient P for the mitigation of soil P depletion. Economic, policy, and infrastructural factors have constrained the use of all fertilizers, including P fertilizer. Given this failure of conventional, seasonal applications of soluble P to be successfully implemented for mitigation of soil P depletion in many smallholder farms in Africa, there is increased need to consider corrective plus maintenance applications of P to increase crop production and prevent further environmental degradation. Replenishment with a large P application could provide immediate rather than only gradual prevention of further soil degradation, even on soils with low to moderate P-sorption capacity. An excessive rate of P for a one-time application of soils with low P sorption capacity, however, might lead to detrimental effects of micronutrient deficiencies and leaching of P.

Accompanying Technologies

Regardless of the option selected for replenishment of soil P, P application by itself will not overcome soil fertility depletion. The replenishment of soil P must be accompanied by technologies such as soil conservation, integrated nutrient management, water harvesting, and control of crop pests and diseases to ensure the increased and then sustained crop production without environmental degradation (see Sanchez et al., 1997, this publication).

Precautions to reduce erosion and runoff may be particularly important on sloping land (Gachene et al., 1997) when combining P application with legume rotations for building soil N capital (see Giller et al., 1997, this publication). Van Bodegom (1995), for example, found increased soil and P loss by erosion when a natural uncultivated fallow was replaced with a planted sesbania fallow in order to replenish N fertility on an Eutrudox with 3% slope in western Kenya. Increased erosion in the sesbania fallow was attributed at least partly to reduced ground cover resulting from removal of weeds during establishment and early growth of sesbania. This observation highlights the importance of maintaining soil ground cover and surface roughness when replenishing erosive soils.

In order to increase and then sustain crop production, replenishment of soil P must be integrated with replenishment of soil N (Giller et al., 1997, this publication) and elimination of other nutrient constraints. Elimination of P deficiency, for example, can lead to limitations by micronutrients (Bationo et al., 1995; Brodrick et al., 1995). Application of high-analysis P fertilizers without S in continuous cropping systems can lead to S deficiencies (Friesen, 1991). Organic-based systems and agroforestry do not eliminate the need for P fertilizer inputs, but the inclusion of organic-based systems in the replenishment of P can have synergism on P availability (Palm et al., 1997, this publication). For example, the application of rapidly decomposable organic material to supply N and K can enhance plant availability of added P (Le Mare et al., 1987) and reduce P sorption (Iyamuremye & Dick, 1996; Ohno & Crannell, 1996).

SUMMARY AND CONCLUSIONS

There is an indisputable need to correct P deficiency in African soils. This can be achieved either gradually with seasonal applications of P fertilizer or rapidly with a relatively large, one-time, corrective application of (i) soluble P fertilizer, (ii) medium- to high-reactive PR, or (iii) low- to medium-reactive PR combined with soluble P. One-time, corrective P applications to reestablish soil P fertility must be followed by periodic, relatively small maintenance applications of P.

Only a few PRs in Africa are currently suitable, both agronomically and economically, for direct application. Partial acidulation of low- to medium-reactive PR has not been adopted commerically, and compaction of low- to medium-reactive PRs with soluble P remains experimental. Many areas of Africa do not have PRs suitable for direct application and will need to rely on imported, high-analysis P fertilizers for the foreseeable future. Areas of Africa with PRs sufficiently reactive for direct application may be able to utilize indigenous PR sources.

Future assessment of PRs should include the comparison of one-time applications of PR with seasonal applications of soluble P fertilizers, including localized placement of soluble P fertilizer in the planting hole at suboptimal rates as practiced by some farmers. The combined application of PRs with soluble P fertilizers as illustrated in Fig. 6-6 also merits investigation. Sufficient data on costs and labor, including extra labor requirements for application of finely ground PR, should be collected in order to enable economic analyses. Field experiments should be of sufficiently long duration (at least 10 yr) to assess the validity of the predicted yield and soil P trends illustrated in Fig. 6-5, 6-6, and 6-7.

Whereas planted tree fallows, legume rotations, transfer of plant biomass, and application of manures have potential to build up soil N capital (Giller et al., 1997, this publication; Palm et al., 1997, this publication), they cannot sufficiently build soil P to overcome P deficiency on highly P-deficient soils. Integration of organic-based systems and agroforestry with P fertilizers, however, can increase P in labile soil P_0 pools and may have potential to enhance the availability of soil P. Encouraging results have been obtained in western Kenya with the integration of tithonia leaf biomass with P fertilizers (ICRAF, 1997; Nziguheba et al., 1998; Sanchez et al., 1997, this publication).

With regard to soil P, a greater understanding is particularly needed on (i) the cycling of P with C and (ii) the mechanisms by which organic materials and enhanced soil biological activity influence P availability. Information should lead to the development of tools for use in decision making on effective options for integration of organic materials and legume rotations with P fertilizers for replenishment and subsequent maintenance of both soil P and N fertility.

The replenishment of soil P must be accompanied with management to overcome N deficiency and other constraints to crop growth. Approaches to building soil fertility must recognize that a major constraint to fertilizer use in small landholdings in Africa is low on- and off-farm income. Many smallholder farmers have lacked the financial resources to purchase sufficient P fertilizer to prevent depletion of soil P. The decision to opt for a large, one-time investment in P application followed by periodic maintenance applications of P should be based on economic, environmental, and infrastructural factors as well as biophysical factors.

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Building Soil Nitrogen Capital in Africa

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ABSTRACT

The dynamic nature of N cycling dictates that soil N capital useful for supplying N for plant growth must be equated with short- to medium-term, rolling capital (the monthly or annual salary), rather than long-term reserves (gold in the bank). Thus building of soil N capital necessitates a focus on the capacity of soils to store organic matter (the principal reserve of N in the soil) and on management strategies to replenish N reserves. For a given climate, the capacity of a soil to store organic matter is directly related to its texture through both direct effects of clays adhering to organic matter and indirect effects on soil aggregation, which render the organic matter protected from decomposition. Some African soils can contain up to 300 to 400 kg N ha^{-1} in free mineral form within the top 2 m of soil, which represents a form of *vulnerable* capital susceptible to leaching. Large amounts of organic inputs are required to build up the soil's capital store of N. The approaches most suitable for this are improved legume fallows, legume-grass leys, or minimum-tillage systems. When soils are cultivated continuously it may be impossible to build up the soil N capital. Even when the capital store of N is replenished, continued use of crop sequences and intercrops with grain legumes and green manures, better integration of crops and livestock, and optimal use of mineral fertilizers are essential to ensure improved fields are maintained. A. major challenge is to work together -with smallholder farmers to find attractive methods for building the N capital of their soils.

Nye and Greenland in West Africa demonstrated that the total stock of C and N in the soil organic matter (SOM), referred to as the soil *capital* store of C and N, declines when soils are cultivated but is gradually restored under natural fallows (Greenland & Nye, 1959; Nye & Greenland, 1960). Of all nutrients, N is required in the greatest quantity for plant growth, and the capacity of soils to supply N to plants is inextricably linked to the amount and nature of the SOM. In this review, we distinguish three main forms of N capital. Mineral N (NH_4-N and NO_3-N) is termed *vulnerable* capital, as it is susceptible to losses and can be equated to *cash in the pocket.* The short- to medium-term capital is the N in the SOM, which is mineralizable in the relatively short term (months) and medium term (1 to 5 yr)—the *monthly or annual earnings.* Long-term N capital is essentially the more recalcitrant part of SOM that contributes relatively little to N supply within 5 to 10 yr—*gold in the bank.* Across much of Africa, soils have come under intensive cultivation only recently as human populations have increased, often leading to greater net losses of SOM due to reduced organic inputs, the faster rate of SOM turnover under cultivation, and increased losses from soil erosion. As a result SOM and the supply of N have declined as natural fallows shortened or vanished, and the short- to medium-term capital store of N has effectively been used up.

The purpose of this chapter is to explore the possible strategies that can be employed to restore the N capital of soils under cultivation in sub-Saharan Africa (hereafter referred to as Africa). There is nothing peculiar about African soils, or tropical soils for that matter. The diversity of soils in the tropics is just as wide as that found at greater latitudes (Sanchez, 1976; Eswaran et al., 1992), although extensive areas of some of the oldest exposed land surfaces occur in Africa, with the resulting highly weathered acid soils. What distinguishes African agriculture, however, is the predominance of agriculturally based economies within which, for a variety of reasons, the use of mineral fertilizers by smallholder farmers is very limited (Heisey & Mwangi, 1996). This is in stark contrast to agriculture in western Europe and North America, where high productivity is sustained and nutrient removal in crops replenished by large inputs of mineral fertilizers or animal manures.

The three principal sources of N for crop production are biological N_2 fixation, organic resources recycled within the cropping field or concentrated from a larger area, and mineral N fertilizers. As N is rapidly cycled through the soil and in many parts of Africa high temperatures and available water favor rapid decomposition, the restoration and maintenance of a capital store of N in soil is particularly problematic. A fundamental question is whether attention must be given to increasing SOM contents to improve the efficiency of N use by crops, or whether it is more appropriate to manage available organic N sources and mineral N fertilizers in relation to crop demand without major emphasis on maintenance of the SOM. Here we discuss the potential for restoration of soil N capital in relation to potential sources of N, management methods, and the ability of soils to store and supply N for crop growth. The most striking conclusion is inevitably that there are no *quick-fix* solutions to maintenance of all forms of N capital, or SOM. Any proposed interventions must generate cropping systems that are productive, sustainable, and economically attractive for smallholder subsistence farmers. The conundrum is that all restorative technologies for improvement of soil fertility without the use of mineral fertilizers involve either import of organic materials from surrounding land or allocation of land to produce organic materials. In the most densely populated areas, land scarcity prohibits the devotion of land to restoration of soil fertility. In such regions methods for replenishment of the short-term capital N store in soils will be hard to find without either some other form of income generation or short-term assistance to purchase fertilizers or direct assistance to compensate for loss of agricultural production, at least in the short term.

TYPES OF CAPITAL: NITROGEN STORAGE IN SOILS

Mineral Nitrogen: Vulnerable Capital

The principal forms of mineral N in soil are NH_4 and NO_3 (NO_2 is present only as a transient intermediate in nitrification). Ammonium can be held as an exchangeable cation on negative charges in soil or as slowly exchangeable (often referred to as nonexchangeable) NH_4. Slowly exchangeable NH_4 is found as an interlayer cation in some 2:1 clays, mainly in vermiculite and illites where it substitutes for K ions that have a similar ionic radius (Nommik & Vahtras, 1982). Release of slowly exchangeable NH_4 is favored by small concentrations of NH_4 and K ions, which would tend to occur in heavily cropped soils. The potential for N storage as slowly exchangeable NH_4 is therefore limited to soils with sufficient amounts of the right clay type, such as the Vertisols (Ayed & Wild, 1983). Jones (1973) found evidence for significant amounts of slowly exchangeable NH_4-N in soils poor in SOM from dry savanna regions in West Africa.

Under aerobic conditions, NH_4 is rapidly nitrified to NO_3 even in acid soils of the tropics, which may contain small numbers of autotrophic nitrifying bacteria (Wild, 1972a). Nitrate is highly mobile in soils and is easily lost by leaching (e.g., Pleysier & Juo, 1981), with estimates of 40 to 50% of the mineralized N being lost under high rainfall environments of West Africa (Mueller-Harvey et al., 1985; van der Kruijs et al., 1988). Leaching of mineralized NO_3-N is not as rapid as that of NO_3-N applied as fertilizer due to the time taken for the NO_3-N to diffuse to the large pores and channels through which water drains preferentially (Wild, 1972b). In acid soils leaching of NO_3-N is retarded due to retention of NO_3 ions by positive charges (Wild, 1972b; Wong et al., 1987). Wong et al. (1990b) demonstrated that the delay in leaching of NO_3 could be predicted from the anion-exchange capacity (AEC) of the soil and that the delay increased with depth in a Nigerian Alfisol as the AEC increased. Assuming that half of the sites were occupied by NO_3, Wong et al. (1990a) estimated that soils with an AEC of 1 $cmol_c\ kg^{-1}$ could hold 140 kg of exchangeable NO_3-N ha^{-1} in the plow layer. The African soils studied had AECs of 0.06 to 0.3 $cmol_c\ kg^{-1}$, which indicates up to 40 kg of exchangeable NO_3-N ha^{-1} might be held in the plow layer. As strongly acid soils rarely contain much 2:1 clay it is unlikely that both slowly exchangeable NH_4-N and NO_3-N retention could be found to any extent in the same soil.

In savanna environments with a pronounced dry season, NH_4-N tends to accumulate during the dry season as nitrification ceases at a water potential just below the permanent wilting point, whereas mineralization proceeds under slightly drier conditions (Robinson, 1957). There is a flush of NO_3-N at the start of the

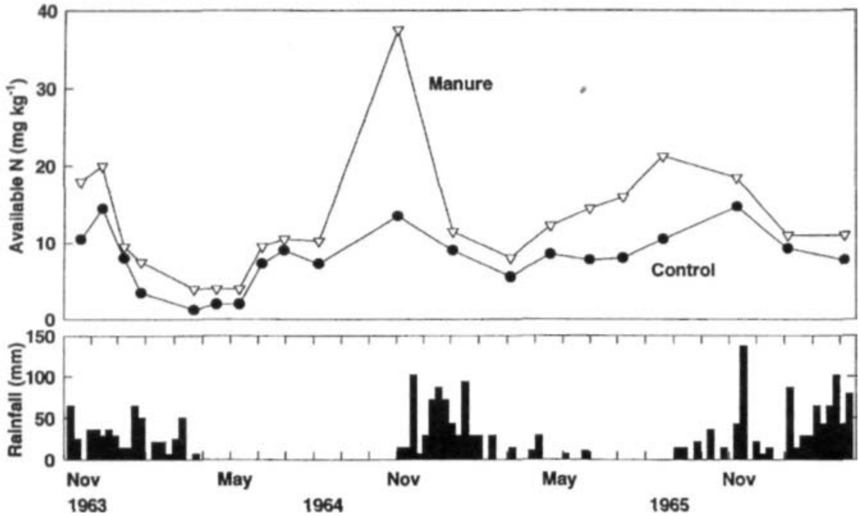

Fig. 7-1. Mineral N in the surface horizons of a sandy granitic soil at Marondera, Zimbabwe, without amendment or with manure added showing the flush of N at the beginning of the rains each year (source Grant, 1967).

rains (Fig. 7-1), commonly known as the *Birch* effect, due to rapid mineralization of killed microbial biomass and labile organic matter released on drying (Birch & Friend, 1956; Birch, 1958; Greenland, 1958; Seneviratne & Wild, 1985) and also to rapid nitrification of NH_4-N accumulated during the dry season (Wild, 1972a). Wild (1972b) found that a bulge of NO_3-N moved slowly down the profile during the rainy season (Fig. 7-2) but that leaching to below 120-cm depth in a bare fallow with approximately 1000 mm of rainfall was substantial only at the end of the rainy season when there was water available for the mineralized NO_3-N to diffuse into the effective drainage channels. Several other early studies showed that large amounts of NO_3-N can accumulate in the subsoil (see Wetselaar, 1962).

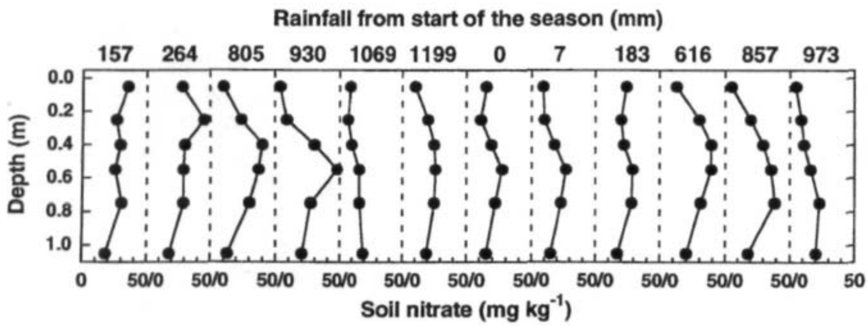

Fig. 7–2. Changes in soil nitrate in the surface 1 m of soil during 2 yr at Samaru, Nigeria (source Wild, 1972b).

increasing recalcitrance, and the resulting SOM is a complex mixture of molecules of plant and microbial origin.

Recent research by Handayanto et al. (1995, 1997) has highlighted the importance of reactive polyphenols in binding proteins. The resulting polyphenol-protein complexes appear to be very resistant to microbial degradation, resulting in poor availability of N for plant uptake from residues that have a narrow C-to-N ratio. It is unclear to what extent complexation of polyphenols and proteins is *a fast route* to SOM formation that could be used to build the long-term soil N capital. Even if this were possible, the complexes formed are recalcitrant and do not appear to act as slow-release fertilizers. Initial experiments in which ^{15}N-labeled residues with a large protein-binding capacity were added to soil indicate that the complexed N is not released over three successive crop cycles /Cadisch et al., 1997, unpublished data).

Analysis of a large database of soils information from Sumatra, Indonesia revealed that there was a strong effect of pH on the soil C content; the minimum C content was found in the range of pH 5 to 6, soils with pH above or below this range tended to have greater soil C contents (Hardon, 1936; van Noordwijk et al., 1997). The precise mechanisms for greater protection of SOM at low pH are not fully understood, but greater amounts of Al in solution and decreased rates of decomposition are likely to be involved (van Noordwijk et al., 1997).

Physical Stabilization

Feller et al. (1991) showed that the amounts of organic C and N stored in West African soils depended on the amount of clay and fine silt-sized particles present, and this is shown for a wide range of African soils in Fig. 7-3. In many acid tropical soils, notably the Oxisols and Ultisols, the clay-size fraction consists mainly of iron (Fe) and Al oxides and in Andisols mainly of allophane. Clay soils in general retain more C derived from plant residues in the long term (Jenkinson, 1977; Amato & Ladd, 1992). Clays are important in direct stabilization of both organic molecules in soil (which are primarily microbial metabolites) and the microorganisms themselves. The exact mechanisms by which clays bind to organic molecules are not fully understood (for a detailed review see Theng, 1979), but the protective effects of clays are certainly due to close adherence between the clays and the organic molecules or the surface of microorganisms. Interactions between clays and proteins (and other organic molecules) are strongly influenced by pH, which affects both *the* cation-exchange capacity of the clays and the organic molecules, for example by changing the conformation of proteins (Theng, 1979). Early research showed proteins were readily degraded when complexed with kaolinite but were resistant to hydrolysis when adsorbed onto montmorillonite (Ensminger & Gieseking, 1942; Birch & Friend, 1956). This led to the suggestion that the protective effect of expanding (2:1) clays was due to the organic molecules becoming entrapped between the clay layers, which could be demonstrated in artificially created, clay-protein complexes in laboratory experiments (e.g., Pinck et al., 1964). Surprisingly, such complexes were not readily found in soils rich in smectite clays, and later research showed that formation of interlayer complexes is likely to occur only under specific, rare conditions; i.e., in strongly acid soils rich in both smectitic clays and SOM (Theng et al., 1986).

Despite this, substantial evidence remains that clays afford protection to microbial proteins, and montmorillonite clays have a greater protective capacity against decomposition than kaolinites (Serensen, 1972). Thus the greater ability of the smectitic clays to protect SOM from decomposition appears to be due both to their greater cation-exchange capacity (CEC) and the larger available surface

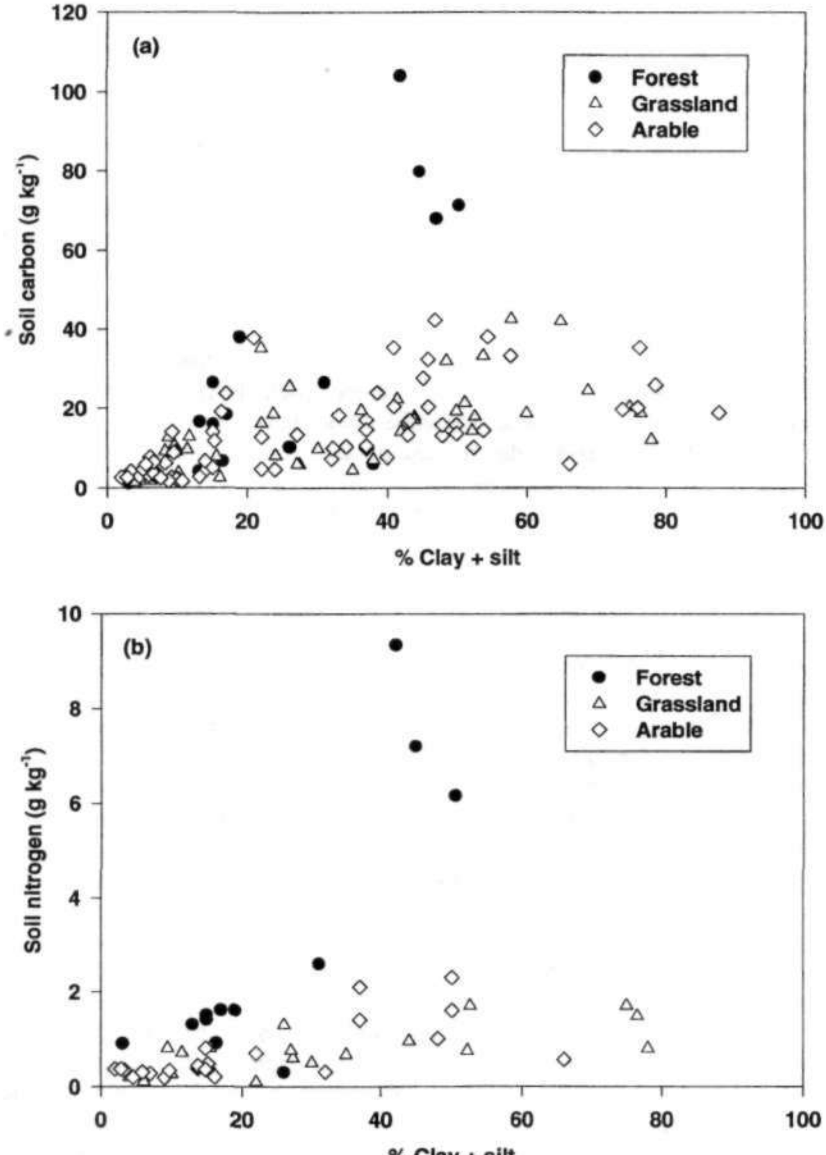

Fig. 7-3. The relationships between (a) soil C and (b) total soil N and (clay + silt) content for soils from Africa (a full list of literature sources is available from the authors).

area for interactions, compared with kaolinitic clays in which the clay layers are held together tightly by H bonding.

From the above discussion we might expect that organic matter is more readily degraded in the kaolinitic (1:1) clays, typical of highly weathered Ultisols and Oxisols in Africa; however, Motavalli et al. (1995) examined N mineralization from tropical forest soils with a wide range of clay contents and mineralogies but, with the exception of the Andisols, found no clear distinction between smectitic and kaolinitic clays. Andisols are highly weathered volcanic soils that have peculiar properties in terms of stabilization of SOM due to the surface interactions between allophane and organic molecules (Boudot et al., 1988), and they characteristically have large SOM contents.

The extent to which plant residues added to soil are protected by clays thus depends on how much of this protective capacity is already saturated (Hassink, 1996). A large part of the *protective* effect of clays results not from interactions between clay and organic colloids but from better aggregation of soil particles (Ladd et al., 1993). Organic residues accumulate within soil aggregates, within pores too fine to allow access to decomposer organisms (Tisdall & Oades, 1982), and microorganisms are sheltered from predation in pores broad enough to allow microbial access but too small for invasion by predatory protozoa and nematodes (Elliot et al., 1980). It is not clear to what extent such structural effects on protection of SOM operate in some tropical soils such as Oxisols and Ultisols in which aggregation is mainly determined by the large amounts of Al and Fe oxides.

Tillage reduces this aggregate-related protection of SOM in both temperate (Bauer&Black, 1981; Robinson etal., 1996) and tropical soils (Lal, 1974, 1976). This results from breaking up soil aggregates and exposing of organic C previously inaccessible and unavailable to decomposer microorganisms rather than from improved oxygen availability (Rovira & Greacen, 1957). CO_2-C is released (Powlson, 1980) and N is mineralized (Craswell & Waring, 1972) as a result of soil disturbance in laboratory experiments, and this is in accordance with the C losses and reduced N mineralization potentials observed when soils are tilled in the field. Losses of mineralizable N exceeded total N losses in various South African rainfed soils (Dupreez & Dutoit, 1995), indicating the exposure of a weakly stabilized SOM pool following tillage. A significant proportion of the soil microbial biomass may be directly killed by soil disturbance (Powlson, 1980) and become available to decomposition; however, the largest fraction of the SOM that decomposes rapidly following cultivation is nonmetabolic and is directly related to decreased soil aggregation.

Water-stable aggregates may be distinguished by the binding agents responsible for their formation into microaggregates and macroaggregates (Tisdall & Oades, 1982). Microaggregates have persistent binding agents consisting of polyvalent metal cations associated with aromatic humic material and strongly sorbed polymers and are resistant to cultivation. Macroaggregates (mainly > 250 μm diameter), however, comprise microaggregates, plant debris, and other organic materials and are held together by transient (microbial and plant-derived polysaccharides) and temporary (roots and hyphae) binding agents. They are disturbed by cultivation and release C and nutrients (Tisdall & Oades, 1982; Elliot, 1986). Recently the plant debris encrusted by clays and occluded in macroaggregates has been identified as the major fraction of SOM that is exposed to decomposition as a result of soil tillage (Oades & Waters, 1991; Golchin et al., 1994a,b). Although the SOM associated with coarse organo-mineral particles shows the greatest losses under cultivation (Tiessen & Stewart, 1983; Zhang et al., 1988), SOM that is stabilized by direct adsorption is probably more resistant to tillage.

The identification of pools of SOM that turn over at different rates has been a major focus of research. Various attempts have been made to identify and isolate fractions of this SOM, which turnover at different rates, based on size and density (Pernet, 1952; Christensen, 1992). These have shown interesting differences between fractions that may be used as indicators of differences in turnover rates between soils. An isolatable *active* fraction that represents the majority of the mineralizable N is likely to remain elusive as net mineralization comes from SOM present in particles of all sizes (Magid et al., 1996). Simulation models of SOM turnover all contain several theoretical pools of SOM, and these can be used to predict the decline of SOM under cultivation.

NUTRIENT CYCLES FROM CROP TO COUNTRY: A QUESTION OF SCALE

In any discussion of balancing nutrient budgets, there is a need to define the scale of the system in relation to inputs and outputs of nutrients. Many studies have calculated nutrient budgets at the scale of an individual field, but recognition that virtually all farming systems depend on nutrient transfers made between fields within a farm, to the farm from the surrounding communal land, between farms, between villages or regions (e.g., Smaling et al., 1993, 1997, this publication) has led to an increased emphasis on nutrient budgets at the farming system or watershed scale. At a coarser scale, *national* nutrient budgets have been calculated for many African countries (Stoorvogel et al., 1993), and international trade results in major transfers of nutrients between continents (Cooke, 1986). In this review, we largely consider the N economy at the scales of the individual farm, including the catchment area for those farms where nutrients are effectively being harvested from the surrounding lands.

African farming systems are diverse with many different carbohydrate staple crops, such as yams *(Dioscorea* sp.), cassava *(Manihot esculenta* Crantz), bananas and plantains *(Musa* sp.) and sweet potato *[Ipomoea batatas* (L.) Lam.], generally in the more humid areas, apart from the widespread cereal crops maize *(Zea mays* L.), sorghum *[Sorghum bicolor* (L.) Moench], and millet *[Pennisetum glaucum* (L.) R. Brown]. Nutrient transfers are of particular importance in mixed crop and livestock systems where animal manure is a major soil amendment, and such systems dominate many savanna regions in West and southern Africa (e.g., Prudencio, 1993). Soil erosion and redeposition may represent a lateral transfer of nutrients between fields, or between farms in different positions in the landscape, or may indeed represent a loss of soil and nutrients to river and lake sediments (van Noordwijk et al., 1997). Soil erosion control structures assist in retaining SOM, and root systems of crops and trees may also capture nutrients in subsurface lateral water flow (Breman & Kessler, 1995). Other transfers away from crop land are made by certain gallery-building termites, and termitaria are often spread in fields by farmers to improve the productivity of their soils (Wood, 1988).

SOURCES OF EARNINGS: METHODS FOR REPLENISHING SOIL FERTILITY

Mineral Inputs

Mineral N is added to the soil in fertilizers or through atmospheric deposition. The typical patterns of restricted mineral fertilizer use in African agriculture described by Bekunda et al. (1997, this publication) occur despite potentially large crop yield responses to moderate fertilizer additions. Where production is maintained by the use of fertilizers, which are generally applied to cash crops, the returns of N and organic materials to the soil in crop residues also can be significantly increased (see below). Animal manures also may contain significant amounts of N in mineral forms (Grant, 1967). In poorly buffered or acidic soils, repeated use of most types of N fertilizers in the absence of other measures to maintain soil pH leads to problems of reduced production due to increasing soil acidity (Djokoto & Stephens, 1961; Bache & Heathcote, 1969; Jones, 1976; Pichotetal., 1981).

It is ironic that atmospheric deposition of N in dust or rainfall tends to be restricted except in close proximity to the major industrial centers, of which there are few in Africa, as the most important source of combined N in the atmosphere is gaseous pollution from transport and industry. The limited information available indicates that between 0.5 and 12 kg N ha^{-1} are contributed on an annual basis from atmospheric deposition in Africa (Jones & Bromfield, 1970; Pieri, 1992), and typical inputs are likely to be at the bottom of this range. Aeolian deposits are especially significant in West Africa where the Harmattan winds result in the redistribution of large amounts of surface soil, although the inputs of organic N have been estimated at only 1.2 to 4 kg N ha^{-1} (Herrmann, 1996).

Organic Inputs: Amounts and Quality

Traditional Fallows and Crop Residue Management

Under natural forest or savanna vegetation, an equilibrium content of SOM is reached that is related to the amounts of organic material added to the soil, the rate of turnover, and the capacity of the soil to retain SOM. Traditionally the burning of vegetation after clearance results in loss of much of the N in the litter and plant biomass, depending on the intensity of the fire. Once land is opened for cultivation, the SOM declines to a new equilibrium content related to reduced amounts of organic inputs, the faster rate of organic matter turnover caused by tillage, and increased losses of SOM due to erosion.

After soil fertility has declined, a long period of natural fallow is required to restore the SOM to its original content (Nye & Greenland, 1960). Restoration of the original N content is due to a number of factors including the lack of removal of N in harvested produce, the gradual concentration of N into the surface SOM due to reduced mineralization rates in the absence of cultivation, greater inputs of more recalcitrant OM, N deposition from the atmosphere, and uptake of N by deeper rooting species, resulting in more efficient capture and recycling of N from deeper horizons. Free-living or root-associated N_2 fixation generally contributes only small amounts of N in agriculture but may be important during long natural fallow periods when availability of C-rich substrates may support higher rates of N_2 fixation in the order of 10 to 20 kg N ha^{-1} yr^{-1} (Giller & Day, 1985).

In agricultural fields, N may be recycled back into the soil in crop residues, both above and below ground, but these are often insufficient to maintain the SOM and the N supply at an adequate content for productive agriculture. In certain traditional practices, poor-quality plant litters are collected from surrounding land. For example, in the *fundikila* system in northern Zambia poor-quality organic material is collected from a large area and composted in situ in mounds of soil both to provide nutrients for crop growth and to reduce effects of toxicity and P fixation in the very acid soils. This has been likened to *recycling poverty* as such cultivation is backbreaking work that often results in pitifully small yields (Dudal & Deckers, 1993). More commonly, approaches to soil N management require inputs of N-rich organic material, such as legume residues and animal manures.

Grain Legumes as Sole Crops and Intercrops

The role of leguminous crops in maintaining soil fertility is well recognized but also has too frequently been uncritically overestimated. Tropical grain legumes can certainly fix substantial amounts of N (Table 7-1) given favorable conditions, but the majority of this N is often harvested in the grain. Legumes such as soybean *[Glycine max* (L.) Merr.] that have been subject to intense breeding efforts are very efficient at translocating their N into the grain, and even when the residues are returned to the soil there is generally a net removal of N from the field (Halvin et al., 1990; Peoples & Craswell, 1992; Giller et al., 1994). Some promiscuous soybean varieties are leafier, have a greater potential to add N to the soil, and are potentially more appropriate for cultivation by smallholder farmers than the recommended varieties grown on commercial farms in southern Africa (Mpepereki et al., 1996). Soybean residues at harvest are lignified (-10% lignin) with C/N ratios around 45:1 and these tend to immobilize N when they are added to the soil (Toomsan et al., 1995). By contrast, groundnut *(Arachis hypogaea* L.) residues can contain >160 kg N ha^{-1}, are less lignified (-5% lignin), and are rich in N, as the crop is harvested while still green. If returned to the soil, groundnut residues can easily lead to doubling of maize yields on sandy soils (McDonagh et al., 1993), but even with groundnut there is a net contribution from N_2 fixation only if the legume stover is returned to die soil or if substantial leaf fall occurs before harvest. The exceptions to this rule are the longer duration grain legumes

Table 7-1. Amounts of N_2 fixed and contributions to soil fertility by grain legumes in Africa (or elsewhere in the tropics in parentheses) grown as sole crops or as intercrops.

Grain legume	Duration	Grain yield	Stover yield	Harvest index	N from N_2 fixation	Amount of N_2 fixed	N in stover	N harvest index	Net input from N_2 fixation	Recovery of stover N	Residual effect in fertilizer equivalents	References†
	d	t ha^{-1}		%		kg N ha^{-1}		%	kg N ha^{-1}	%	kg N ha^{-1}	
Arachis hypogaea												1
Sole crop	90-140	0.8-2.7	1.4-6.7	25-47	38-62	20-70	52-154	30-70			0-97	
	(106-119)	(0.3-3.1)			(47-92)	(37-297)	(74-166)		(13-100)	(12-26)		
Intercrop	(105)	(0.8)	(3.9)	(21)								
Cajanus cajan												2
Sole crop	90					2-92					67	
	(140-241)	(1.1-1.4)	(1.8-7.1)	(8-31)	(4-88)		(12-50)	(21-68)			(40)	
Intercrop		(0.6)	1.8			12					20-89	
Glycine max												3
Sole crop		1.7-2.6			65-89	159-227	50	80			0-22	
	(97-104)	(2.4-3)	(2.4-3.1)	(50)	(0-97)	(0^50)	(30-67)	(80-87)	(-37—46)	(14-23)		
Intercrop		(0.1-0.8)										
Phaseolus vulgaris												4
Sole crop	72	0.1-2.2	0.1-6.2	21-64	10-51	2-58	3-38	44-70				
	(114)	(1.6-4)	(4-7.5)	(35-56)	(0-71)	(0-85)						
Intercrop	(70-90)	(0.5-1.5)	(1.7-3)	(31^9)								
Vigna unguiculata												5
Sole crop	69-115	0.2-1.4	0-4	9-42	8-89	11-201	20-94	29-66		12-24	140-205	
		(1.5-2.7)	(5.2-8.4)	(22-34)	(12-77)	(9-125)		(64)		(12)		
Intercrop	150						43					
		(1-1.9)	(3.3-5.8)	(26-35)	(61-69)	(18-73)	(59-73)					

† 1: Balasubramanian and Nnadi, 1980; Bationo etal., 1991; MacColl, 1989; McDonagh etal., 1993; Suwanarit etal., 1986; Toomsanet al., 1995; Wetselaar and Ganry, 1982; 2: Dalai, 1974; Jones and Wild, 1975; Kumar Rao and Dart, 1987; MacColl, 1989; Cobbina, 1995; Mandimba, 1995; 3: Wetselaar and Ganry, 1982; Suwanarit et al., 1986; Ofori and Stern, 1987; MacColl, 1989; Sisworo et al., 1990; Toomsan et al., 1995; 4: Jones and Wild, 1975; Davis and Garcia, 1983; Davis et al., 1984; Ssali and Keya, 1984b, Ssali and Keya, 1986; Castellanos et al., 1996; Amijee and Giller, 1998; Giller et al., 1998; 5: Agboola and Fayemi, 1971; Balasubramanian and Nnadi, 1980; Eaglesham et al., 1982; Ssali and Keya, 1984a; Ofori et al., 1987; Van Kessel and Roskoski, 1988; Ntare et al., 1989; Sisworo et al., 1990; Bationoo et al., 1991; Franzluebbers et al., 1994; Klaij et al., 1994; Reddy et al., 1994.

such as pigeonpea *[Cajanus cajan* (L.) Millsp.] and varieties of cowpea *[Vigna unguiculata* (L.) Walp. sp. *unguiculata]*, which may lose a substantial amount of biomass in the form of roots and leaves that fall before harvest (Giller & Cadisch, 1995). A sole pigeonpea crop drops up to 40 kg N ha^{-1} in fallen leaves during its growth (Kumar Rao et al., 1983), and its small harvest index means that a relatively large proportion of the fixed N remains in the field (Table 7-1), which can give a substantial benefit to subsequent crops. But virtually all the information that we have on contributions from N_2 fixation is from research conducted on experimental stations where the crops have been adequately fertilized with P and other nutrients, and often irrigated (Giller & Wilson, 1991).

As biomass and yields of sole-cropped grain legumes under smallholder conditions in Africa are often small (<500 kg ha^{-1} of grain), the amounts of N_2 fixed are barely significant. For example, in the Usambara Mountains in northern Tanzania, where bean *(Phaseolus vulgaris* L.) is the staple grain legume, most farmers' crops lacked nodules because of severe P deficiency, and amounts of N_2 fixed were estimated to be as little as 2 to 8 kg N ha^{-1} (Amijee & Giller, 1998; Giller et al., 1998). Adding fertilizers to alleviate the P deficiency resulted in substantial enhancement of nodulation; however, only when K fertilizers were also supplied were grain yields raised to 1000 kg ha^{-1} or more at most sites (Smithson et al., 1993), which would result in roughly 50 to 60 kg N ha^{-1} from N_2 fixation. Amounts of N_2 fixation by grain legumes also can be severely constrained by drought, and Ganry (in Wetselaar & Ganry, 1982) found that N_2 fixation by groundnuts over three years in Senegal was almost linearly correlated to total rainfall.

Intercropping of grain legumes generally results in the legume deriving a greater proportion of its N from N_2 fixation than when grown alone, but legume dry-matter production and N accumulation are usually reduced because of competition from the companion crop (e.g., Nambiar et al., 1983) so that the overall amount of N_2 fixed is less (Table 7-1). Cowpea intercropping was advantageous when intercropped with maize or millet in seasons with adequate rainfall, but the cowpea competed strongly with the cereal crop for soil water when rainfall was limiting (Shumba et al., 1990; Franzluebbers et al., 1994). One notable exception again is pigeonpea, which has a phenology complementary to that of most cereal crops. As the initial above-ground growth and development of pigeonpea is very slow, there is little direct competition between the crops (Dalai, 1974). The long duration of traditional pigeonpea varieties and their ability to root deeply allow the pigeonpea to grow on after the companion cereal crop has been harvested, utilizing residual water in the soil; however, although sole pigeonpea gave clear residual effects on growth of subsequent maize, the residual effects of maize-pigeonpea intercrops were not substantial (Kumar Rao et al., 1983, 1987), presumably because of reduced inputs of N. Despite claims for substantial *transfer* of N for grain legumes to companion cereal crops, the evidence indicates that benefits are limited and largely due to *sparing* effects (Giller et al., 1991). Benefits are more likely to accrue to subsequent crops as the main transfer pathway is due to root and nodule senescence and fallen leaves (Ledgard & Giller, 1995).

Improved Fallows: Green Manures and Agroforestry Species

Direct benefits from N_2 fixation are obviously greater when herbaceous or shrubby legumes are grown specifically to improve soil fertility as green manures or *planted fallows* (Tables 7-2 and 7-3). Amounts of N accumulated by the legume are generally determined in the short term by the rate of establishment of the legume, and subsequently by the productivity of the legume and the length of the growing period for the green manure or planted fallow.

Early reports of experiments successful in maintaining crop yields using green manures resulted from testing of a rather limited selection of species such as mucuna *[Mucuna pruriens* var. *utilis*[x] (L.) DC], pigeonpea, *Crotalaria* sp., and *Canavalia* sp. across a wide range of environments (e.g., de Sornay, 1918; Davy, 1925). Green manures such as sunnhemp *(Crotalaria juncea* L.) were exploited extensively to maintain soil fertility on commercial farms in Zimbabwe until mineral N fertilizers became widely available (Rattray & Ellis, 1952). The dense cover formed by creeping legumes such as mucuna and kudzu *[Pueraria phaseoloides* (Roxb.) Benth.] leads to self-shading and senescence of leaves giving a dense mat of organic matter. Inputs of N from such species based solely on measurements of standing crop may be underestimated substantially (van Noordwijk & Purnomisidi, 1992). Significant N benefits in yields of subsequent crops have been reported even when mucuna was burned to ease land preparation (Vine, 1953), supporting the suggestion that large amounts of N were contributed to the soil from roots and fallen leaves.

Early examples demonstrated the successful use of planted green manure fallows in restoring soil fertility more rapidly than regeneration of the native vegetation (e.g., Jaiyebo & Moore, 1964). It also was quickly recognized that although green manures gave greater yields of subsequent crops than rotation with grain legumes such as groundnut, "they suffer the handicap of occupying the land unproductively for a whole year" (Brown, 1958). Thus additional benefits such as improved weed control or other uses are generally necessary for farmers to spontaneously adopt use of green manures (see below). There has recently been a resurgence of interest in the use of short-term, planted fallows using shrubby legumes such as sesbania *[Sesbania sesban* (L.) Merr] and tephrosia *(Tephrosia vogelii* Hook.f.), with demonstration of substantial gains in crop yields (Kwesiga & Coe, 1994; Sanchez et al., 1997, this publication).

Intercropping with Green Manures or Trees

Intercropping and relay cropping of legume green manures have the advantage that crops are still produced while organic material is produced for soil amendment. The obvious disadvantages are that the green manures or trees may compete with the crops, and that the amounts of organic material produced are generally less than when the land is devoted to soil improvement (Tables 7-2 and

' The taxonomy of *Mucuna* is confusing and there are many species in this pan-tropical genus, but the nonstinging varieties used in agricultural experimentation invariably belong to this species (R. Polhill & B. Verdcourt, 1996, personal communication; Wulijarni-Soetjipto & Maligalig, 1997).

Table 7-2. Amounts of N_2 fixed and contributions to soil fertility by green manure legumes in Africa (or elsewhere in the tropics in parentheses) grown as sole crops or as intercrops (b).

Green manure legume	Duration	Stover yield	N from N_2 fixation	Amount of N_2 fixed	N in stover	N contributed belowground	Recovery of stover N	Residual effect in fertilizer equivalents	References
	d unless stated	t ha^{-1}	%		kg N	ha^{-1}	%	kg N ha^{-1}	
Arachis repens					111-161		0-17		18
Cajanus cajan	(90H20)	2.2-3.3 b) 2.1-3.7	(65)		49-142				8,6
Calapogonium mucunoides	1yr	I.3-4.3 b) 4.1-5.7		(64) 126-182	(65)			23-31	19, 12,20
Canavalia ensiformis	(120)	9 b)4.8 b) 3.4-5.1			(142-206)				5,9
Centrosema acutifolium	(120)	(1.1-1.3)	(72-82)	(33-43)	(49-56)	(3)			4
Centrosema macrocarpum	(120-1 yr)	(0.8-12.7)	(65-83)	(19-11)	(30-51)	(4)			4, 11
Centrosema pascuorum	1yr	0.05-1.9							23,24
Centrosema pubescens	100-1 yr	1.9-3.4 (1.4-12.3)	(50)	67-136 (80-280)	99-130 (36-257)	(13-15)	0-51	5-13	12, 18,20,25
Chamaecrista rotundifolia	3yr	0.15-0.4							23
Crotalaria juncea	28-90	(2.4-9)			(63-198) b)247				12, 16,22
Crotalaria ochroleuca		2.5-9.1			35-291	0-27	26-44	90	9,22
Desmodium canum	(1yr)	(2.4-6)		(45-107)	(12^19)			25	
Desmodium heterophyllum	1yr	b) 1.5-3.2		64-110				22-34	20
Desmodium ovalifolium	100 (120)	1 (1.1-1.5)	(44-70)	(11-25)	26 (25-36)	(7)			4, 12
Lablab purpureus	100-150	0.9-8 b)3							3,9

(continued on next page)

Table 7-2. Continued.

Green manure legume	Duration	Stover yield	N from N_2 fixaton	Amount of N_2 fixed	N in stover	N contributed belowground	Recovery of stover N	Residual effect in fertilizer equivalents	References†
	d unless stated	t ha^{-1}	%	kg N ha^{-1}			%	kg N ha^{-1}	
Macroptilium atropurpureum	1 yr	b) 2.5–5.0	(78–87)	46–167				**b) 38**	20
				(23–137)					
Mimosa pudica	1 yr	b) 1.3–1.8		43–83				**12–37**	20
Mucuna pruriens var. *utilis*	(120)–140	1.3–5.6			110				5, 8, 9, 12,
		(3.4–8.5)			(71–283)				16, 21
Neonotonia wightii	(1)–9 yr			(126)	146–314	146			10
Pueraria phaseoloides	100–1 yr	2	(68–92)		62	(3)		**23–31**	4, 20
	(120)	b) 4.1–5.7		136–182	(71–132)				
		(1.9–3.8)		(9–115)					
Psophocarpus palustris	100	1			42–134		2–48		12, 18
Sesbania cannabina	(45–55)	(3.1–7.3)	(70–93)	(119–209)	(98–163)				16, 19
Sesbania rostrata	(44–61)	(1.5–12.4)			(62–307)				15, 16
Sesbania sesban	30–60	0–0.6	13–18	7–18	(83)				4
	(60–84)	(4.3)	(84)	(92)					
Stylosanthes capitata	(120)	(0.4–1.3)	(76–87)	(12–38)	(16–44)	(3)			4
Stylosanthes guianensis	1 yr	a) 2–10	63–75	(7–47)	(43–64)	(3)			4, 23
	(120–1 yr)	(1.4–2)	(75–97)						
Stylosanthes hamata	1 yr	0.15–3		0–212	50				7, 14, 23, 24
Stylosanthes macrocephala	(120)	(0.6–2.7)	(84–88)	(14–71)	(17–80)	(4)			4
Tephrosia		b) 6.8–8			112–203				8
Vicia sativa	150	8							8
Vigna luteola	1 yr	b) 1.2–2.9			31–126			42	20
Vigna radiata	(40)				(70–80)		(35–50)		2, 17
Vigna unguiculata	100–150	0.7–3.7			45			(66)	1, 2, 3, 12,
	(40–90)	(2.1–6.9)			(49–113)				13, 16
Zornia glabra	(120)	(1.2–2.1)	(77–88)	(28–61)	(39–71)			(3)	4

† 1: Agboola and Fayemi, 1972b; 2:Agboola and Fayemi, 1972a; 3: Bartholomew et al., 1992; 4: Cadisch et al., 1989; 5: Cahn et al., 1993; 6: Cobbina, 1995; 7: de Leeuw et al., 1994; 8: Drechsel et al., 1996; 9: Fischler, 1997; 10: Gethin Jones, 1942; 11: Grof, 1986; 12: Hairiah, 1993; 13: John et al., 1992; 14:Kouamé et al., 1993; 15: Kwesiga and Coe, 1994; 16: Meelu et al., 1994; 17:Morris et al., 1986; 18: Mulongoy and Akobundu, 1985; 19: Patel et al., 1996; 20: Reynolds, 1982; 21: Sanginga

Table 7-3. Amounts of N_2 fixed and contributions to soil fertility by shrubs and trees in the tropics.

Tree legume	Duration	Amount of N_2 fixed	N from N_2 fixation	Pruning N input	Fertilizer equivalent	Referencesf
	d	kg N ha"'	%	——kgNha"[1]——		
Acacia auriculiformis			52-66	37-97		5, 13
Acacia erioloba			21			17
Acacia hebeclada			16			17
Acacia hereroensis			49			17
Acacia holosericea	200	3-6	30	10-20		1
Acacia karroo			25			17
Acacia kirkii			19			17
Acacia mangium			52-66	26-97		5, 13
Acacia mellifera			71			17
Acacia reficiens			22			17
Acacia torlilis			13			17
Calliandra calothyrsus	90-360	11-377	0-87	87-220		5, 13, 14
Casuarina equisetifolia	90	166	65-90			8, 15
Dichrostachys cinerea			49			17
Erythrina poeppigiana				153	110	7
Faidherbia albida			2	20-32		6, 12, 17
Flemingia macrophylla	85-360			149-352	103	10, 19
Gliricidia sepium	85-360	170-204	26-89	63-500	45-101	4,5,8,9,10, 13, 14, 18, 19
Leucaena leucocephala	85-360	76-274	34-100	54-577	43-183	4,5,7, 10, 15, 18,20
Paraserianthes falcataria			55	43-183		3, 13
Pericopsis angolensis	85				116	10
Prosopis glandulosa			30			17
Senna siamea	85-360	0	0	128^175	85	2, 3, 5, 10, 19
Sesbania formosa	360			18-32		5
Sesbania grandiflora	360		78-86	60-286		4, 5, 13
Sesbania rostrata	87	64-109	77-100	83-230		10,20
Sesbania sesban	360			19-37	60-134	9

1: Comet et al., 1985; 2: Danso and Morgan, 1993b; 3: Danso and Morgan, 1993a; 4:Duguma et al., 1988; 5: Duguma and Tonye, 1994; 6: Dunham, 1989; 7: Haggar et al., 1993; 8: Ladha et al., 1993; 9; Matthews et al., 1992; 10; McDonagh et al„ 1995; 11: Mwiinga et al., 1994; 12: Okorio and Maghembe, 1994; 13: Peoples et al., 1991; 14: Peoples et al., 1996; 15: Sanginga et al., 1986; 16: Sanginga et al., 1989; 17: Schulze et al., 1991; 18: Tian et al., 1993; 19: Yamoah et al., 1986; 20: Yoneyama et al. 1990.

7-3). Whether intercropping with green manures and trees is advantageous thus depends on the balance between the benefits and the costs.

The net benefits may vary significantly between sites and seasons, depending on the availability of water and nutrients, and the unpredictable nature of the interactions between the green manure and the crop adds a risky complication. Relay planting can reduce the likelihood of competition with the crop where rainfall is limited, with the production of the green manure restricted by its ability to use residual water after the main cropping season. Hedgerow intercropping or alley cropping has been very useful for developing a better understanding of tree-crop interactions (i.e, see van Noordwijk, 1996; Vanlauwe et al., 1996), but its applicability in smallholder agriculture still remains to be demonstrated because of strong crop-tree competition and the intensive management required

(Young, 1989; Sanchez, 1995). An exception may be on steeply sloping lands, where hedgerows can be planted on contours to help prevent soil erosion.

The traditional agroforestry practice of farmers who maintain trees such as faidherbia [*Faidherbia albida* (Del.) A. Chev.] in their fields is well documented as a means for maintaining fertile *islands* of soil around the trees (Dancette & Poulain, 1969; Vandenbeldt, 1992). The extent to which this practice actually develops rather than maintains soil fertility is still unclear. Similar effects are seen under the canopies of other N_2-fixing trees such as *Acacia* species and also under trees that cannot fix N_2 (Belsky et al., 1993; Breman & Kessler, 1995), and the extent to which N_2 fixation contributes to this phenomenon needs detailed investigation. Root systems of trees in arid lands can scavenge for water by being very extensive, extending up to 50 m from the trees in some species (Soumare et al., 1993) or by rooting deeply. The potential for intensification of tree planting with species such as faidherbia to enhance the soil N status will depend on the relative importance of N_2 fixation or N acquisition from a wide area in the enhancement of soil fertility (Giller & Cadisch, 1995). If there is significant N_2 fixation that is deposited on the soil surface through leaf fall then current natural stands of trees could be intensified substantially.

Animal Manures

Cattle manure is an integral component of soil fertility management in many regions of Africa. The beneficial effects of manure on soil fertility are well documented, and crop responses to manure application are often due more to the contribution of P and cations such as Ca and Mg than the addition of N (Hartley, 1937; Grant, 1967) or due to physical effects of SOM addition on water infiltration and retention (Mugwira & Murwira, 1997); however, crop responses to manure application observed in farmers' fields are highly variable due to differences among farmers and between regions in the chemical composition of the manures, in the rates of manure application, and in the frequency of application on each field.

The nutrient contents of manures differ due to variation in the animals' diet and in particular due to differences in the ways manure is collected, supplemented, and stored. In regions with a long dry season, the quality of grazing available is often much better during the rains or after fire, resulting in a larger N content in the manure. Powell (1986) found that dry-season manure had an N content of 6 g kg^{-1} of dry matter compared with 18.9 g kg^{-1} during the early rainy season, when the quality of diet had improved. The diet also may influence the partitioning of N between feces and urine; feeding high-quality diets (containing little lignin and polyphenols) results in more N being excreted in the urine than in the feces (Reed et al., 1990; Somda et al., 1995). Feeds rich in tannins increased the amount of N excreted in the feces as compared with urine, where N is often quickly lost through volatilization. Recent results indicate that the N in manures from animals fed with tannin-rich diets is very resistant to mineralization in soil (P.L. Mafongoya, 1997, unpublished data).

Animal management has an important influence on the amount of manure collected and its N content (Table 7–4). There are two principal systems for

Table 7-4. Nitrogen contribution from different animal manures in Africa.

Type of manure	Country	System	Application rate	N applied	Reference!
			t ha-[1]	kgNha-'	
Cattle	Nigeria	Transfer	0.4	4.3	8
Cattle	Burkina Faso	Transfer	1.6	20	8
Cattle	Nigeria	Transfer	4.5	54	11
Cattle	Zimbabwe	Grazing in fields	1.11	1.7	7
Cattle	Zimbabwe	Confinement of herds in fields overnight	6.9	41	7
Cattle	Kenya	Transfer	38-168	236-638	9
Compost	Tanzania	Transfer	15	45	5
Cattle	Zimbabwe		13-29	191-683	4
Farmyard manure	Nigeria	Transfer	1-2	10-20	3
Cattle	Zimbabwe	Transfer/communal areas	10	109-190	6
Cattle	Zimbabwe	Transfer	0.03-5.4	0.3-48	1
Cattle	South Africa	Transfer	6	180	2
Cattle	Cote d'lvoire		1.2-4.5	15-58	10

t 1: Campbell et al., 1997; 2: Grant, 1967; 3: Hartley, 1937; 4: Karigwindi et al., 1996; 5: Le Mare, 1972; 6: Murwira, 1995; 7: Powell and Mohamed-Saleem, 1987; 8: Powell and Williams, 1993; 9: Probert et al., 1995; 10: Quilfen and Milleville, 1983; 11: Rodel et al., 1980.

manure collection from animals: Those in which animals are penned continuously and the manure is collected, stored, and transported to the cropped fields, and those where animals are allowed to graze in grazing areas during the rains and graze freely during the dry season but are corralled at night. In some situations animals are corralled on the cultivated field between harvest time and time of cultivation of the next crop. This system is better economically in terms of manure transport, and the effects on soil fertility are generally greater because of the inputs from urine. As cattle that are corralled often graze extensively over large areas, the collection of manure represents an enrichment of fertility from a wide area onto the field where the manure is used. Storage of manure before application to the field has been shown to influence the N content of the manure. Ammonia may be lost rapidly by volatilization from manures (Murwira, 1995). When manure was stored in heaps or in pits until application, the buried manure had substantially greater contents of N, P, and K (Kwaye, 1980). Addition of crop residues or straw to manure reduced N losses, and there is certainly scope to improve manure management to enhance its value in supplying nutrients in synchrony with crop demand. In many regions, however, there are strong demands to use or sell crop residues for fodder or as building materials.

Surprisingly, the beneficial effect of manure on N availability for maize grown in granitic sandy soils was due to N released directly after application (Fig. 7-1). This N was most likely present as free mineral N in the manure as mineralization studies have shown that the poor-quality manures found in Zimbabwe lead to a prolonged period of N immobilization (Murwira & Kirchmann, 1993). Yield responses to manure can be seen in crops for several years after application when the manure is supplied in sufficiently large amounts (Mugwira & Murwira, 1997).

Table 7-5. A classification of soil improvement systems indicating above- and belowground inputs (presence or absence of inputs are denoted by + or -).

	Simultaneous	Sequential	Cut-and-carry
Grain legumes	Row/strip intercropping	Crop rotations	Residue transfer
Shoots	+	+	+
Roots	+	+	-
Green manures	Row/strip intercropping	Green manuring	Biomass transfer
Shoots	+	+	+
Roots	+	+	-
Fast-growing trees	Alley cropping, boundary planting, interspersed trees	Rotation fallow	Biomass transfer
Shoots	+	+	+
Roots	+	+	-
Animals	—	Grass/arable leys	Stall-feeding/corralling manure application

Sandford (1989) estimated that 16 to 47 ha of grazing land were required to produce sufficient manure for sustained maize production of 1 to 3 t ha^{-1} in a semiarid environment in West Africa. It is clear that there is insufficient manure to sustain even such moderate yields in many parts of West Africa (Fernandez-Rivera et al., 1995; Williams et al., 1995). There also is a danger of long-term degradation of grazing lands, as there is substantial nutrient removal over prolonged periods. In Burkina Faso farmers' rates of manure application were measured at 2.5 to 41 ha^{-1} yr^{-1} (Quilfen & Milleville, 1983). Considering cattle confined in *bomas,* Probert et al. (1995) calculated that manure available in Machakos, Kenya was sufficient to supply cropland with only 2.5 t ha^{-1} annually although much larger rates in excess of 38 t ha^{-1} were applied by farmers to a few fields. In a sandy soil in Niger a large part of the N applied in manure was translocated to depths below 1.5 m after application of 13 t ha^{-1} of manure, indicating that smaller, more frequent applications may be a more effective way of using manure (Brouwer & Powell, 1995). Thus although manure is an important source of nutrients for crop growth in many cropping systems in Africa, it is widely acknowledged that insufficient manure is available to support crop production.

Provision of Organic Inputs

In summary, there are three basic ways of producing organic inputs rich in N for use in soil fertility improvement: crop sequences or fallows with grain legumes or green manures; *simultaneous* intercropping systems where crops and green manures are grown together; or biomass transfer or *cut-and-carry* systems. Animals also play a role in converting N-poor crop residues into somewhat richer sources of N. All of these methods for producing biomass can be used with either herbaceous green manures or with fast-growing trees (Table 7-5). Apart from the cut-and-carry systems, N is added to the soil from leaves that fall during growth, from shoot material returned to the soil when the plants are harvested, and from roots and root exudates. The amounts of N returned below ground are difficult to quantify and therefore very poorly documented, but often they represent the only input of organic residues to the soil. The major problem with all these different approaches to providing organic resources is the limited quantity available unless a substantial investment of land, and labor and other nutrients are committed to their generation.

BUILDING SOIL NITROGEN CAPITAL

Can We Build Soil Nitrogen Capital?

Given the susceptibility of mineral forms of N (the vulnerable capital) to losses by leaching and gaseous losses, strategies for building soil N capital must be focused on the short- to medium-term N capital in the SOM. As discussed above, the capacity of a soil to store organic matter (referred to as the *equilibrium level* by Nye & Greenland, 1960) is determined largely by the soil's texture and soil pH (van Noordwijk et al., 1997). This maximum capacity to store organic matter relates to the amount of organic residues, microbial biomass, and microbial metabolites that can be stabilized. While this storage capacity may be exceeded by applying extremely large amounts of organic inputs, rapid turnover of unprotected organic matter (including turnover of the microbial biomass itself, Ladd et al., 1995) will lead to loss of this *excess* organic matter unless it is continually replenished. The relationship between clay and silt content and the soil C and N contents is illustrated in Fig. 7-3. In clay-rich soils the amount of C and N is highly variable, depending on the quantity of organic inputs (often related to rainfall) and the land use and in particular on the intensity of cultivation. The soil C and N content under forest soils can be much greater than soils under grassland or arable cultivation because of surface accumulation of *unprotected* organic matter in the surface horizons. Sandy soils invariably contain a small amount of C and N, irrespective of the land use, because of their lack of capacity to protect organic matter from microbial degradation. Therefore, the degree to which the organic matter content (and hence the soil N capital) can be built up depends on how much of the protective capacity of the soil is already saturated (Nye & Greenland, 1960, p. 53; Hassink, 1995b).

The positive effects of SOM on crop growth are many (e.g., increasing porosity, infiltration, resistance to erosion, ease of root penetration) and do not solely depend on the capacity to supply N or other nutrients (de Ridder & van Keulen, 1990). In the granitic sandy savanna soils of Zimbabwe, which have roughly 5 g kg^{-1} organic C and a N content below 0.4 g kg^{-1}, Grant (1967) concluded that SOM was a minor source of N for maize growth and that supplementation with mineral fertilizers or manure was essential to ensure reasonable yields even in the short term.

Application of large amounts of N-poor residues, highly lignified residues, or residues rich in polyphenols may allow accumulation of amounts of SOM above the clay-determined storage capacity, but this will lead to relative enrichment of the SOM with chemically recalcitrant, passive pools. As such pools must be relatively inert to allow them to accumulate, it is unlikely that they can contribute much directly to N availability for crops, although there will be other benefits from the effects of increased SOM on soil structure.

Literature on tropical soils abounds with statements that suggest that SOM contents cannot be replenished under cultivation because of thesis/ *rate of oxidation.* There are examples where SOM has been increased, depending on the amount of organic residues returned to the soil. For example, Bache and Heathcote (1969) demonstrated that the addition of cattle manure at 2 t ha^{-1} for 15 yr led to small increases in soil C (from 2.4 to 4.3 g kg^{-1}) and N (from 0.21 to 0.34 g kg^{-1}) contents at Samaru, Nigeria, and Pichot et al. (1981) found that annual applications of 60 t ha^{-1} of cattle manure increased soil C from 2.5 to only 6.6 g kg"[1] after 18 yr at Saria, Burkina Faso. At Kabete, Kenya, addition of 10 t ha"[1] of cattle manure combined with return of all crop residues failed to prevent a decline in the SOM contents in an Alfisol cropped annually to maize and beans (Kapkiyai, 1996; Smaling et al., 1997, this publication).

The potential effects of different cropping patterns and residue management on equilibrium SOM contents are illustrated by modeling exercises based on the data of Siband (1974) for millet cropping systems in Casamance, Senegal (Fig. 7—4 and 7-5). The simulations indicated that return of crop residues had a negligible effect on the amounts of soil C (Fig. 7-5a). Rotation with groundnut where all stover was returned to the soil had only a small impact on soil C but helped to maintain better millet yields in the alternate years in which it was grown. Addition of 1 t ha^{-1} of cattle manure increased production, but to maintain soil C at contents close to those found under the forest, annual application of 5 t ha^{-1} of cattle manure was required: much more than is available in most African cropping systems. The simulations suggest that the addition of 45 kg N ha"[1] annually to the millet gives an initial boost in amounts of soil C, but that this

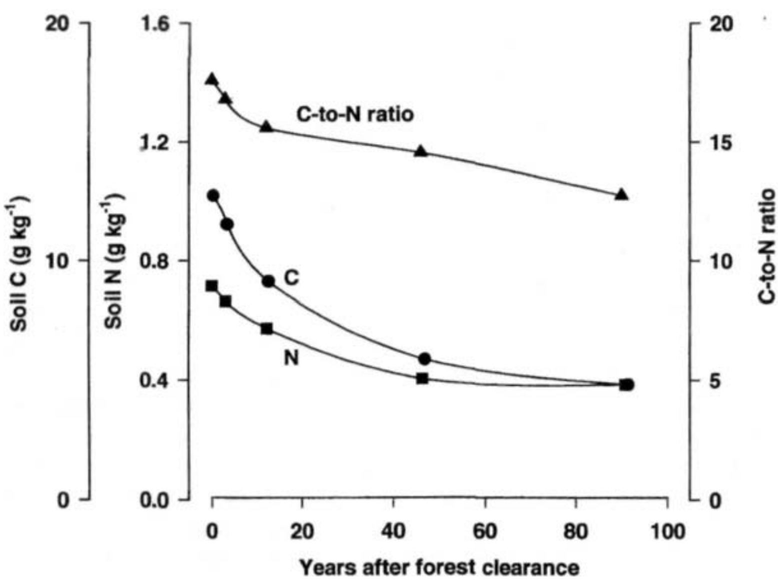

Fig. *1-A.* Changes in soil organic matter with length of cultivation in a red soil in Casamance, Senegal. Soils (pH 6.1, clay 12 to 14%) were sampled from profiles in five fields that had been under cultivation for different lengths of time ranging from undisturbed forest (0 yr) to 90 yr.

amount of N is insufficient to maintain production and organic inputs, as the initial SOM is turned over more rapidly with cultivation. A grazed ley system with the pasture legume stylo *[Stylosanthes guianensis* (Aublet) Sw.; which has shown potential in such regions, Tarawali & Peters, 1996)] maintained a higher equilibrium C because of the relatively lignified residues, the longer growing period, and a small proportion (10-25%) of the fixed N exported in animal products (Fig. 7-5b). If the land was cropped to millet for 50 yr before groundnut and complete crop residue retention were introduced (Fig. 7-5c), the increases in soil C were much less than where these changes were initiated from the start (Fig. 7-5a). This indicates a hysteresis between SOM depletion and restoration because of the poor growth of crops when the soil becomes badly degraded and SOM contents are substantially reduced. Although these interventions are simulated and do not include the likely effects of increased soil erosion when the soils become degraded, this exercise illustrates the need for combined approaches to increasing N inputs using legumes, fertilizers, and animal manures if available.

Managing Nitrogen-Poor Crop Residues

Crop residues poor in N, such as the cereal stovers, are the major sources of organic materials produced in most smallholder food production systems in Africa and therefore are arguably an important resource for maintaining the organic matter contents of soils. Such residues are often burned to aid plowing and assist in pest control.

Because of their wide C/N ratio and relatively large amounts of C that are readily available for microbial growth, a prolonged immobilization of N in the microbial biomass is induced, which deprives crops of available N during the early growing season. Thus although recycling cereal stover to cropped lands may help to maintain SOM contents, or increase them in degraded soils with the associated benefits of improved soil structure, the short-term N supply must be managed to allow productive cropping. This can be done by use of mineral fertilizers or by addition of other organic resources rich in N, but sufficient amounts of readily available N must be added to satisfy the immobilization potential of the cereal straws and allow production of both grain and stover. After 3 yr of incorporating millet straw, a significant increase in soil N mineralization was observed and there was a significant increase in the soil N content (Pichot et al., 1974), although the amount of straw applied (10 t ha^{-1}) was equivalent to 3 yr of actual straw production in the system, assuming that all of the straw was returned to the soil. Key questions are how long a period is required before a net benefit is seen after cereal straw incorporation and how much straw should be incorporated.

An alternative approach is to compost all cereal stover or feed it to animals to avoid problems of N deficiency in crops sown soon after residue incorporation. *Both* composting of crop residues and feeding to animals help to improve the quality of soil amendments and hence the ease of handling as the nutrients are in a more *concentrated* form; however, composting is labor intensive, involves N losses, and is more likely to be feasible for maintaining productivity in home gardens.

Reduced Tillage

Minimum or zero tillage are further ways by which the SOM store can be increased under intensive cropping. Lack of tillage generally leads to a greater equilibrium SOM content because of better conservation of organic residues

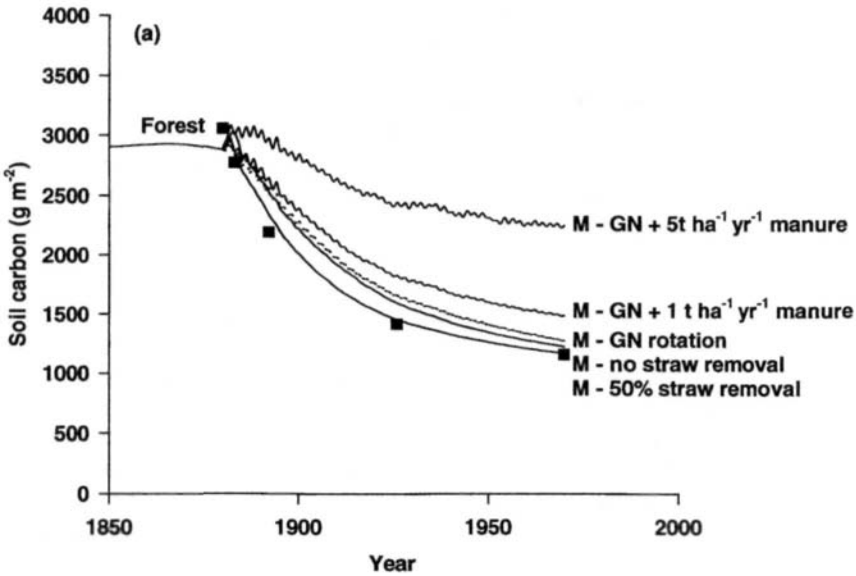

Fig. 7-5. Simulation modeling of changes in soil organic C in a sandy soil at Casamance, Senegal, based on the data (symbols) of Siband. Simulations were run for various scenarios.'

' Cropping management patterns imposed after forest clearance: (a) millet monocropping with all stover returned or 50% straw removal, millet-groundnut (GN) rotation with all residues returned and without cattle manure or with cattle manure at the rates of 1 or 5 t ha"'; (b) the millet monocropping with 50% straw removal and the millet-groundnut (GN) rotation with all residues returned and 1 t ha^{-1} cattle manure are shown for comparison together with simulations run for monocropping of millet fertilized with 45 kg N ha^{-1} and a 1 yr millet-1 yr stylo *(Stylosanthes guianensis)* grazed ley rotation; (c) 60 yr millet monocropping with 50% straw removal, followed by millet monocropping with all residues returned and the millet-groundnut (GN) rotation with or without 1 t ha"^{1} cattle manure. Modeling exercises were done using the CENTURY model (Version 4.0) where soil organic matter (SOM) dynamics are principally based on a three-pool model (active pool = *2x* microbial biomass C; slow pool = approximately 50% of total soil C and passive pool). The model includes a nutrient limited feedback mechanism on crop growth and stover production where nutrient demands (defined as crop-specific maximum C/N ratios of young tissue) are not matched by N mineralization or inputs of N. Initial SOM content was obtained by using local climate and soil conditions under a simulated forest situation until steady state conditions were reached (=200 yr). Thereafter a clearing year was introduced with plowing and soil cultivation activities. Subsequently the model was run with different cropping options for 90 yr. All crop plantings were preceded by plowing. Unless otherwise indicated all crop residues were left in the field in the case of millet and groundnut or 50% were removed for alternative uses. Where manure or fertilizer was applied, this was done before planting. In the case of the millet-stylo ley system the legume was grazed lightly (assuming no effect on subsequent growth) three times (manure was deposited in the field). The large effect of the stylo on SOM build up is due to (i) the longer growing period than that of the crops, (ii) lack of straw removal, and (iii) a higher lignin content (lignin in stylo was allowed to vary from 10 to 25% depending on plant age whereas lignin in the crops varied from 6 to 12%).

within the field, greater physical protection of residues due to the lack of cultivation, and reduced losses of SOM through erosion. This gradually leads to an increased SOM and soil N content, which is achieved through reduced rates of N release. Several experiments in Alfisols of West Africa have demonstrated greater SOM and total N contents in soils under zero tillage compared with cultivation after only 2 to 4 yr (Kannegieter, 1968; Lal, 1974, 1976). Yields of maize and

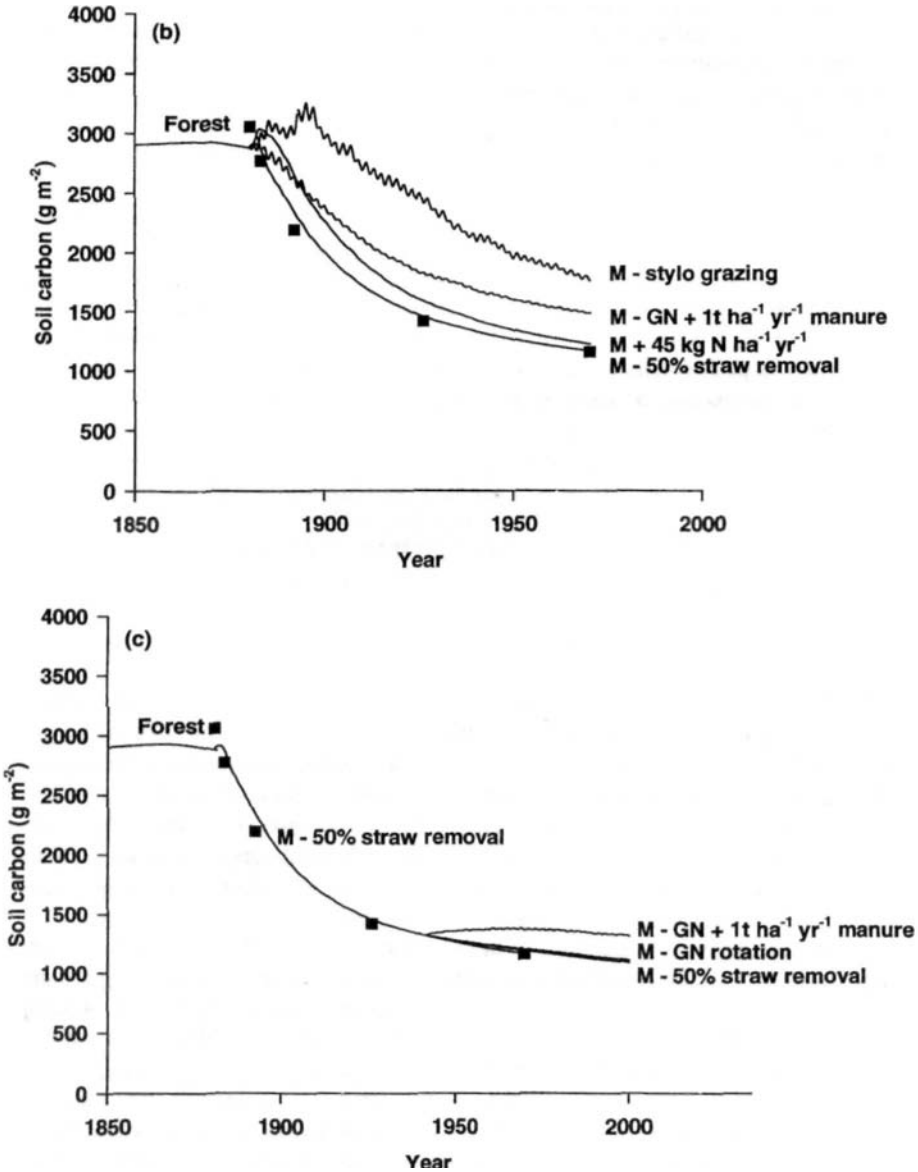

Fig. 7-5. Continued.

legumes were similar in untilled and cultivated plots to which recommended rates of N fertilizers were added (Lal, 1974, 1976). No comparisons were made in these studies on the effects of reduced tillage without mineral fertilizer inputs, and weed control was achieved by using herbicides in untilled plots (Lal, 1976), representing an additional external cost. Dalai (1989) found increases in soil C and N contents in the top 10 cm of a fine-textured Vertisol in tropical Australia after 13 yr of zero tillage when all residues were returned but the increased N contents were marked only when mineral fertilizers were applied; however, on another Vertisol small differences in soil C and N contents were found between zero tillage and conventional tillage after 8 yr in only the surface 2.5 cm, even with N fertilizers and return of all crop residues (Dalai et al., 1995). Similarly, Nyborg et al. (1995) achieved a net addition of N to the soil after 11 yr of barley *(Hordeum vulgare* L.) cropping only when fertilizer N was applied to increase plant biomass production.

Thus a substantial improvement in SOM content will be necessary before the net benefits due to mineralization from the larger amount of SOM outweigh the reductions in the net amounts of N mineralization. Other inputs, such as using N fertilizers or legume cover crops and herbicides for weed control, also will be required. In fact, large benefits in crop production are likely to be found only if full tillage is periodically reintroduced after a long period of reduced tillage, and tillage operations can be used as a strategic way of mining accumulated N for crop production.

IMPROVING THE ECONOMY: MANAGING THE SOIL NITROGEN SUPPLY

Increasing Nitrogen Inputs

Unfortunately there are no miracle cures for the restoration or maintenance of soil fertility. The use of mineral fertilizers by smallholder farmers is commonly restricted (see other chapters in this publication), and used alone, mineral fertilizers can lead to (or exacerbate) problems of soil acidification unless corrective measures also are taken (e.g., Kwaye et al., 1995; Bekunda et al., 1997, this publication). Organic resources also are generally in limited supply. The above discussion indicates that substantial amounts of N-rich organic materials are required to make a significant impact on crop yields.

All methods for generation of organic material for soil amendment depend on allocation of land, potentially resulting in a loss of crop yield. Only where marginal land that cannot be used for agricultural production land is used, or land is used at a time when no crops could be grown, is there no penalty in lost yields. Even when land is used for grazing, not enough is available to produce the amounts of animal manure required to sustain crop production. To date there is limited use of forage legumes or ley farming systems in African smallholder agriculture that would both increase the fodder available (and hence both the quantity and quality of manure) and contribute to soil fertility directly.

In some parts of Africa, due either to very dense human populations or the incidence of trypanosomiasis, cattle are only a minor component of agriculture and manure is not an option for crop fertilization. In such situations fallowing or green manuring are the most suitable methods for production of organic inputs. There are abundant examples in the scientific literature where green manures have been shown to be useful for maintaining soil fertility (e.g., Jaiyebo & Moore, 1964; Kwesiga & Coe, 1994), although use of such practices by farmers is limited. The reasons for lack of adoption of green manures are complex, although the extra labor involved in managing a green manure and the unpredictable responses are often cited as reasons. Very often the necessary stage of farmer experimentation and testing of green manure technologies has never been carried out, which might have allowed for farmer innovations and modification of technologies. Smaling and Fresco (1993) calculated that 50% of the arable cropping land in one district of Kenya would have to be devoted to green manuring to balance the N outputs.

Where land is very scarce, the intercropping of green manures and cereals may be the only feasible means for generating organic inputs. In this case the interplay between the reduction in cereal yield caused by competition from the intercropped green manure and the residual benefit in yield from the contribution of N returned to the soil in the green manure biomass is critical. For a significant effect on cereal yields in a subsequent year the *absolute* minimum green manure biomass required would be in the order of 40 kg N ha^{-1} (roughly 21 ha^{-1} dry matter). As approximately 20% of the N from a high-quality green manure residue is recovered by the first crop (Giller & Cadisch, 1995), this is likely to give a yield benefit of only 500 kg ha^{-1}. Given that the farmer has had to wait for a year to realize this extra yield, then the yield loss that has to be tolerated in the first season is less than that returned in the following season. A longer-term residual benefit from the green manure may compensate for the initial competition with the main cereal crop, but as long-term benefits from addition of high-quality organic materials tend to be small it is often hard to quantify such gains. There are examples where intercropped or relay-cropped green manures produced 81 ha^{-1} of biomass (Table 7-2) although whether such inputs are achievable under farmers' conditions remains to be tested.

Similarly, a 2-yr planted fallow may give treble the yield of continuous maize in the same season, but the cumulative maize yield during 3 yr gives virtually no advantage (Kwesiga & Coe, 1994), although residual benefits of the fallow may extend for two to three subsequent crops. Unless there is no shortage of agricultural land for crop production, the yield benefit after a green manure fallow must be substantially greater than that which could have been grown in three consecutive crops. But if land is abundant, there is perhaps little incentive to increase the yields from a given area.

Improving Nitrogen Recycling Efficiency in Cropping Systems

Apart from the N conservation that can be achieved by recycling crop residues to the soil, there is substantial scope for increasing the efficient capture of mineral N. Much emphasis has been focused on the concept of enhancing the synchronization of N release from organic resources with crop demand for N, and this is undoubtedly important in very wet climates with high-potential leaching risks; however, in the seasonally dry climates that prevail over much of Africa, large amounts of mineral N are present in soils at the onset of the rains. Wild (1972b) emphasized the need for early growth of crop roots to capture the N released in this flush. The common practice among farmers of planting with the first rains could partly be in recognition of this, and simple interventions such as avoiding deficiencies of other major nutrients could help in ensuring good root growth. Planting of crops on ridges can also help to reduce N leaching as much of mineralized or added N is in the raised topsoil, and the majority of leaching occurs due to water collecting and entering the soil in the furrows (van Noordwijk, 1989; Itimu, 1997).

Obviously the deeper that roots penetrate later in the season the more $N0_3$-N can be recaptured from those depths. Losses of N from leaching were reduced to almost nothing under mixed perennial crops compared with maize under a high-rainfall climate, mainly because of the constant presence of a deep rooting system (Seyfried & Rao, 1991). In annual cropping this could be mimicked through relay cropping with pigeonpea or other deep-rooted cover crop species that may capture free NO_3-N from deeper horizons. The N could then be returned to the soil in the legume residues at the beginning of the next growing season. Soils with an appreciable anion exchange capacity tend to be highly leached and dominated by Al, which may form an effective chemical barrier to root penetration by many crops or trees; however, the soils in western Kenya have appreciable NO_3 retention capacity, but Al saturation is below 10%, and fast-growing agroforestry trees such as calliandra {*Calliandra calothyrsus* Meissner) and sesbania have substantial root length at depths well below those reached by maize (Mekonnen et al., 1997; Jama et al., 1998). Amounts of $N0_3$-N and water were significantly reduced in the subsoil compared with those found under maize monoculture, suggesting that the trees were effective in capturing NO3-N that would otherwise have been leached (Hartemink et al., 1996; Mekonnen et al., 1997). Such trees could therefore be effective ways of reducing N losses (particularly where there is subsurface lateral water flow) and returning N to the cropping system if forms of management sufficiently attractive to smallholder farmers can be found.

It also is possible that substantial amounts of mineral N may occur in deep water tables, which are accessible to very deep-rooting (tree) species in arid climates (Buresh & Tian, 1997). Roots of faidherbia and some *Acacia* species have been shown to reach water at depths of up to 40 m (Dupuy & Dreyfus, 1992) but the amounts of mineral N that occur at such depths are not well documented.

Combined Use of Organic and Mineral Resources

Initial results examining the interaction between mineral N and organic residues using ^{15}N-labeled urea indicate that there is no bonus to be gained in terms of increased fertilizer N use efficiency by mixing mineral and organic inputs at moderate rates of addition (Itimu et al., 1997, unpublished data). Only when sufficient organic material has been added to have significant effects on soil

Structurere, nutrient retention, and root penetration is there likely to be increased efficiency in the use of mineral fertilizer (Palm et al., 1997, this publication).

CONCLUSIONS

Large Additions of Organic Matter or Repeated Inputs?

Fallowing, whether natural or planted, is really the only way to enhance the SOM capital store of N, as other sources of organic materials are in limited supply. If large amounts of organic manures are added to soils there is a danger that the protective capacity of the soil may be exceeded, leading to wastage due to rapid decomposition and losses of the mineralized N by leaching, volatilization, or denitrification. Further, if the capital store of N in SOM is built up, there will always be the temptation to *spend from the bank* by tillage or liming to stimulate N mineralization and release.

Simply improving the efficiency with which nutrients are recycled within existing cropping systems cannot alone give the increments in SOM or soil N supply necessary to raise crop production to respectable yields. Repeated additions of high-quality organic residues or mineral fertilizers or both are necessary to increase and maintain crop production. Indeed, a prerequisite for efficient nutrient cycling is a sufficiently deep and dense rooting system to ensure that available N is captured. A certain degree of soil fertility is necessary to ensure this, and where crop yields are already poor, inputs of N and other nutrients into the cropping system are necessary to enhance early crop growth and allow capture of free NO_3-N at depth.

The urgency of solutions to meet the growing demand for increased productivity dictate that extra N must be brought into the cropping systems, and this can be provided through the use of fertilizers or through addition of fixed N_2. No single solution can, or should, be recommended, as interventions need to be tailored to, and developed jointly with farmers with due regard to their wide diversity of farming systems, cultures, and needs. The diversity of soils and soil fertility status between fields within single farms or villages also must be recognized and exploited to allow gradual implementation of soil fertility restoration strategies.

Critical Targets for Future Research

Long-Term Soil Fertility Experiments

The number of long-term experiments in which there is adequate detailed information on the effects of continuous organic residue applications on soil N build up is still limited for different climates and soils in Africa. Carefully planned and managed trials on land representative of soils in farmers' fields are necessary to establish the long-term effects of new interventions on crop production and soil fertility (Greenland, 1994). Most experimental stations were established and remain on the more fertile soils, and much of the information cited in this review is derived from them. Experiments on more representative soils are required to give a much more secure basis for modelling exercises (e.g., Fig. 7-5) to explore the likely effect of different management on the capital store of N in soil.

Farmer-Focused Research

As we have argued earlier (Giller & Cadisch, 1995), there is perhaps sufficient understanding of both the processes and the resources that are available for the enhancement of soil fertility to make an impact. Yet mere is sparse evidence for use of this knowledge in smallholder farming in Africa, at least in part because improvement of soil fertility requires a substantial investment of resources (whether financial for the purchase of mineral N fertilizer or in terms of land and labor for the growth or collection of organic manures). The recent resurgence of interest in the use of cover crops such as mucuna in Benin does not represent a new intervention: this had been tried with success by experimenters in West Africa much earlier, who expressed dismay at the lack of implementation by smallholders (e.g., Dennison, 1959). The adoption of mucuna green manuring by smallholders indicates that the idea was highlighted by researchers at a time when it fitted farmers' needs well. Indeed the ability of mucuna to establish and grow quickly and smother imperata grass *[Imperata cylindrica* (L.) Rausch.] has been the main reason for farmers' interest (Versteeg & Koudokpon, 1992). By contrast, the direct fertilizer effect of mucuna was the primary benefit highlighted by farmers in Honduras although they also recognized the advantages of the reduced labor requirements for weeding and improved water conservation (Buckles, 1995). Rehabilitation of imperata-infested land has also been the main reason for recommending mucuna in Southeast Asia, where die predominance of acid, P-fixing soils means that large doses of phosphate rock were required together with mucuna to allow productive cropping for several years (von Uexkull & Mutert, 1994).

Better mechanisms are required for sharing of knowledge among all of those involved—farmers, researchers, extension agents, and NGO workers—in trying to improve productivity of smallholder agriculture. Many of the agricultural researchers and extension officers in Africa (including authors of this chapter) come from small village communities, and the gap of understanding is not as wide as we often imagine. Flow of knowledge cannot be achieved through a narrow prescriptive approach but requires development and testing of a battery of possible interventions for soil fertility improvement suited to the specific agroecological environment together with farmers. Enhanced networking among soil fertility researchers in Africa represents a significant recent development [e.g., the African Network for Biological Management of Soil Fertility (AfNet) and the Soil Fertility Network for Maize-based Cropping Systems in Southern Africa (Soil Fert Net)] and many attempts are currently being made to improve communication with NGOs and farmers.

Targeting Solutions

Even within narrow geographic regions a large variability exists in soil fertility such that even for adjacent fields the most suitable interventions for farmers might differ. A soil fertility replenishment strategy may best be directed specifically to address the rehabilitation of unproductive fields, as these can be left for several years under planted fallows or legume-based leys, and as the incremental response to addition of mineral fertilizers or high-quality organic residues may be greater in slightly less degraded lands (Fig. 7-5a and 7-5c). Where pressure for crop land is intense, interventions to improve soil fertility may be best targeted to the fields where the farmer has little potential yield to lose (Versteeg & Koudokpon, 1992). It is fairly common to see unproductive fields planted even though the investment of seed is scarcely warranted, presumably to visibly maintain ownership or for other reasons. If crops are already failing to yield on certain fields, then there is little loss to the farmer to break the cycle and use a legume cover crop or shrub for one or more seasons to boost productivity or rehabilitate the land for cropping. This approach has a potential disadvantage in that if the land is severely degraded, the soil fertility investment required to restore productivity is likely to be much greater and there is a risk that even the most robust legumes may not grow.

Often only one legume has been recommended for soil fertility improvement when many other species or accessions of those species tested might be more suitable. In many African countries researchers are still investigating the same species tested as early as the 1920s, yet in the genus *Crotalaria* alone there are more than 480 species with 85 subspecies (Polhill, 1982). While it is possible that the best legumes were already identified, recent major efforts at germplasm collection and testing for acid soils, for example at CIAT (1993) has led to the identification of many new species and accessions. From knowledge of their adaptation and performance elsewhere, a list has been developed of forage legumes that would be worthwhile testing immediately in various environments in Africa (Thomas & Sumberg, 1995), many of which are useful as green manures. Improved access to information on cover crops through the use of databases (e.g., Weber et al., 1997) may assist in identification of potentially useful species.

If a soil fertility replenishment strategy is envisaged in which farmers are offered external assistance, then such interventions could be targeted for poorly productive fields and the farmers recompensed for the loss of yield during the restorative period. Whether such an approach will survive the period during which assistance is offered is highly questionable considering past experiences of various projects, but this probably depends on how robust and successful the intervention is in restoring soil fertility. Even if the soil fertility is restored, careful management to conserve nutrients and continued inputs of N are necessary to sustain production at acceptable yields.

The potential interventions that will most quickly lead to the build up of the short- to medium-term N capital of the soil are: planted legume fallows, legume-based ley systems, and animal manures. When land pressure dictates that fields cannot be rested, other means of replenishing the N supply are needed. For the maintenance of soil fertility under continuous cropping, repeated inputs of N must be assured to maintain productivity through legume rotations, intercropping or relay cropping with green manures, animal manures, and mineral fertilizers.

Our knowledge of the importance of soil textural properties in the ability to store SOM, and hence N capital, should guide our targeting of these different approaches: sandy soils are going to require more frequent additions of high-quality organic material or mineral N fertilizers or both to sustain yields. Soils with a greater clay content and better structure might better be managed using periodic boosts to productivity such as short-term planted fallows due to their better ability to protect SOM, again together with some mineral fertilizer inputs and well-planned tillage operations.

The urgent problem of poor crop productivity due to depleted soil fertility in many parts of Africa demands that ideological stances that favor the sole use of organic resources or the sole use of mineral fertilizers are cast aside. Supplies of even poor-quality organic resources for soil amendment are limited, and mineral N fertilizers are undoubtedly required to ensure food production. The integrated efforts of all concerned are required to find attractive solutions to the problem of building the soil N capital for future generations of African farmers.

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8 Combined Use of Organic and Inorganic Nutrient Sources for Soil Fertility Maintenance and Replenishment

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ABSTRACT

The beneficial effects of combined organic and inorganic nutrients on soil fertility have been repeatedly shown, yet there are no guidelines for their management. Organic materials are not *magic;* many of their functions with respect to soil fertility are known. Organic materials influence nutrient availability (i) by nutrients added, (ii) through mineralization-immobilization patterns, (iii) as an energy source for microbial activities, (iv) as precursors to soil organic matter (SOM), and (v) by reducing P sorption of the soil. The challenge is to combine organics of differing quality with inorganic fertilizers to optimize nutrient availability to plants. Numerous field trials indicate both added benefits and disadvantages of combining nutrient sources. Increased nutrient recovery and residual effects are associated with combined nutrient additions compared with inorganic fertilizers applied alone. Unfortunately, for many trials there is lack of crucial information on the nutrient content and quality of the organic inputs. Trials are needed that link the quality of the organic material to its fertilizer equivalency and its effect on the longer term composition of SOM and crop yields. A systematic framework for investigating the combined use of organic and inorganic nutrient sources includes farm surveys, characterization of the quality of organic materials, assessment of the fertilizer equivalency value based on the quality of organics, and experimental designs for determining optimal combinations of nutrient sources. The desired outcome is tools that can be used by researchers, extension-

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ists, and farmers for assessing options of using scarce resource for maintaining soil fertility and improving crop yields.

The impact of soil fertility replenishment projects (Sanchez et al., 1997, this publication) is likely to be limited to a small number of farmers in the near future until appropriate programs and policies are put in place. More immediate strategies using farmer-available resources are needed that could reach more farmers, sooner. Although fertilizers are used in much of sub-Saharan Africa (hereafter referred to as Africa), the amounts applied are insufficient to meet crop demands (Smaling et al., 1997, this publication). Organic inputs are often proposed as alternatives to mineral fertilizers (hereafter referred to as inorganic fertilizers); however, the traditional organic inputs—crop residues and animal manures—cannot meet crop nutrient demand over large areas because of the limited quantities available, the low nutrient content of the materials, and the high labor demands for processing and application. Most farmers in Africa fall within the two extremes of the organic to inorganic fertilizer continuum and use a combination of organic and inorganic inputs (Table 8-1). Crop yields still fall short of their potential because of inadequate nutrient inputs, the inappropriate quality of the organic materials, and inefficient combinations.

This chapter deals with the combined use of organic and inorganic nutrient sources for meeting crop demands and maintaining or restoring soil fertility. Given the high cost and uncertain accessibility of inorganic fertilizers in much of Africa, the goal should be to provide as much of the nutrients as possible through organic materials, making up the shortfall of the limiting nutrients through inorganic fertilizers. These goals would change as inorganic fertilizers became more affordable or available. The beneficial effects of the combined use of organic and inorganic nutrients on soil fertility, crop yields, and maintenance of SOM have been repeatedly shown in field trials, yet there are no predictive guidelines for their management, such as those that exist for inorganic fertilizers.

The success of combined nutrient management depends on several factors, including the availability and affordability of different types of inorganic fertilizers, the types and quantities of organic materials available, and the rates and proportions at which the two nutrient sources are combined. Most studies have included animal manures and crop residues as the organic additions while there

Table 8-1. The use of nutrient inputs at selected locations in sub-Saharan Africa.

	Location					
Nutrient source	Western Ugandaf	Central Ugandat	Western Kenyat	Central Kenyat	Mutoko Zimbabwe++:	Shurugwi Zimbabwe++
	% of farmers					
Inorganic fertilizers	3	4	54	83	98	40
Manures	29	31	79	98	86	65
Crop residues	4	83	72	98	77	

t Source, Bekunda and Woomer (1996).
++ Source, Murwira et al. (1995).

has been relatively little research on the use of alternative, higher quality organic resources, such as leguminous cover crops and agroforestry species.

A systematic approach that includes organic materials of different qualities and their combinations with inorganic nutrients is needed to develop guidelines for the selection and efficient management of these scarce resources. In the following sections, the effect of organic materials on nutrient availability and crop production is reviewed from both scientific and practical perspectives. This review is followed by examples of combined nutrient management from field experimentation and modeling that could provide a framework for immediate field application and future research.

EFFECTS OF ORGANIC MATERIALS ON NUTRIENT AVAILABILITY AND ACQUISITION

Organic inputs can influence nutrient availability (i) by the total nutrients added, (ii) by controlling the net mineralization-immobilization patterns, (iii) as a source of C and energy to drive microbial activities, (iv) as precursors to SOM fractions, and (v) through interactions with the mineral soil in complexing toxic cations and reducing the P sorption capacity of the soil. In addition to these direct effects on nutrient availability, organic materials can affect root growth, pests, and soil physical properties that in turn influence nutrient acquisition and plant growth. The net effect of these different mechanisms on nutrient availability and plant growth differ with climatic regime, soil type, and quality and quantity of organic inputs.

Sources of Nutrients

Organic inputs such as manures, cover crops, and green manures have generally been assessed in terms of their N concentration, while relatively little attention has been paid to other macronutrients and micronutrients present. Organic inputs should be considered as complete fertilizers (N-P-K), perhaps the best being those containing or releasing the nutrients in the ratios and rates required by crops.

Nutrient Contents

The nutrient contents of organic materials, ranging from crop residues to agroindustrial wastes, vary widely. Table 8-2 compares the nutrients contained in a variety of organic materials with the nutrients required to produce a modest 2-t crop of maize *(Zea mays* L.) grain plus 3 t of stover. Although all the nutrients in the organic materials will not be available to a crop, the information can be used for an initial assessment of the type and amount of organic materials that are appropriate for a given cropping system and yield goal. These estimates can then be adjusted, knowing that crop recovery of N supplied by high-quality leguminous green manures is rarely more than 20% (Giller & Cadisch, 1995) while that recovered from lower quality cereal stovers is generally much lower.

Table 8-2. Average nutrient contents on a dry matter basis of selected plant materials and manures collected in eastern and southern Africa.

Material+	N	P	K
	— kg t^{-1} —		
Crop residues			
Maize stover	6	<i	7
Bean trash	7	<l	14
Banana leaves	19	2	22
Sweet potato leaves	23	3.6	-
Sugarcane trash	8	<1	10
Coffee husks	16	4	-
Refuse compost+	20	7	20
Animal manures			
Cattle§			
High quality	23	11	6
Low quality	7	1	8
Chicken	48	18	18
Farmyard chickenj	24	7	14
Leguminous tree (leaves)			
Calliandra calothyrsus	34	2	11
Gliricidia sepium	33	1.5	21
Leucaena leucocephala	34	1.5	21
Sesbania sesban	34	1.5	11
Senna spectabilis (non-N_2-fixing)	33	2	16
Nonleguminous tree and shrubs (leaves)			
Chromolaena ordorata	38	2.4	15
Grevillea robusta	14	<1	6
Lantana camara	27	2.4	21
Tithonia diversifolia	36	2.7	43
Leguminous cover crops			
Crotalaria ochroleuca	42	1.6	9
Dolichos lablab	41	2.2	1.3
Mucuna pruriens	35	2.0	7
Nutrients required by 2 t maize grain + 3 t stover	80	18	60

† The TSBF database is the source of all data unless otherwise noted.
‡ Source, Nandwa (1996, unpublished data).
§ Source, Mugwira and Mukurumbira, 1984.
¶ Source, Sommers and Sutton, 1980, not from Africa.

Some organic materials such as poultry manures contain sufficient nutrients in 1 to 2 t for a 2-t maize crop, while others such as crop residues can require at least 10 t to match that contained in the 2-t maize crop. Cattle manure varies tremendously in its quality and fertilizer value. Extremes are found in manure obtained from commercial dairy farms compared with that from the communal areas of Zimbabwe (Mugwira & Mukurumbira, 1984). It is the latter, low-quality manures, that predominate on smallholder farms of Africa (Probert et al., 1995). In comparison, many leguminous trees and cover crops contain sufficient N in 2 or 3 t of leafy material (Giller et al., 1997, this publication).

As a general rule, many organic materials when applied in modest amounts, i.e., <5 t dry matter ha^{-1}, contain sufficient N to match that of a 2-t crop of maize but they cannot meet P requirements and must be supplemented by inorganic P in areas where P is deficient (Palm, 1995).

Organic Materials, Adding or Recycling Nutrients?

For organic materials to offset the nutrients removed from crop harvest, it is essential to differentiate between (i) organics produced on site and involved only in recycling of nutrients and (ii) organics produced elsewhere and carried to the site (biomass transfer), which count as an actual addition of nutrients. Recycling of nutrients on site may serve as a nutrient buffer to the system but will not redress the problem of nutrient depletion; nutrients are essentially being mined, except for cases of N_2 fixation.

On the other hand, biomass transfer is not widely practiced, except in cases where there is abundant animal manure available (Smith et al., 1993). Even the role of biomass transfer in redressing nutrient depletion must be evaluated at a scale larger than the plot because nutrients are being added to one location at the expense of another. For example, Swift et al. (1989) calculated that 96 kg N in manure, approximately 10t of low-quality manure, is needed to maintain 2 t ha"^{1} maize yields. Expressed on an areal basis, 14 to 42 ha of miombo woodland grazing land are needed to supply that quantity of manure on a sustainable basis; at higher grazing levels the system is being mined and is no longer sustainable. The use of urban and agroindustrial wastes can reverse the flow of nutrients from crop harvest back to the farm, but this is probably not financially justified in most cases. A recent study in Kenya showed that 1 kg of N and P from compost costs US$ 0.50 and 1.20, respectively, compared with US$ 0.42 and 1.18 for N and P in purchased inorganic fertilizer (N = 200 g kg^{-1} and P = 90 g kg^{-1}; S.M. Nandwa, 1996, unpublished data).

Quantities of Organic Materials Available to Farmers

How do the amounts of organic materials needed to meet crop nutrient requirements compare with the amounts available to farmers? Average millet [*Pennisetum glaucum* (L.) R. Br.] stover production of 1.3 t ha^{-1} in the Sahel is less than the 2 t of mulch recommended (Bationo et al., 1995). Crop residues also have competing uses, primarily as feed for livestock, that reduce the amounts available for managing soil fertility. An average of <700 kg ha^{-1} of manure, ranging from 450 to 1600 kg ha^{-1}, is available for semiarid West Africa. This is much less than the 3 to 7 t ha^{-1} recommended for replenishing nutrients removed by crop harvest (Fernandez-Rivera et al., 1995). Manure production by zero-grazed cattle in Kenya has been estimated as 1 to 1.5 t $animal^{-1}$ yr-^{1} (Strobel, 1987). Two animals would be needed to supply a 2-t maize crop, if the manure were of high quality, but eight animals would be required if the quality was low (Table 8-2).

Increasingly the traditional nutrient sources for soil fertility management are produced in insufficient quantities and quality to meet crop demands. Alternative higher quality sources must be found, but there must also be niches on farms or the vicinity where they can be produced (Garrity & Flinn, 1988). Leguminous plant materials provide higher quality organic inputs to meet N demands, if not P, but incorporating nonfood legumes in the farming system requires a sacrifice of space or time that is normally devoted to crop production. The additional labor requirement for planting, transporting, and incorporating these materials is also high (Ruhigwa et al., 1995). Therefore, farmers have not widely adopted planting legumes to improve soil fertility (Garrity & Flinn, 1988; Giller & Wilson, 1991). The economic and social trade-offs of improved soil fertility using legumes and other high-quality organic materials must be properly assessed in comparison with using crop residues and animal manures.

Regulators of Mineralization-Immobilization Patterns

Decomposition and nutrient release patterns are determined by climatic, edaphic, and resource quality factors (Swift et al., 1979). Of these factors, resource quality is most easily managed by farmers. Considerable research over the past century has related N release patterns to the resource quality, or chemical characteristics, of organic materials (Heal et al., 1997). The N concentration and the C-to-N ratio of the material still probably serve as the most robust indices when all plant materials are considered (Constantinides & Fownes, 1994). Nitrogen concentration in tissue ranging from 18 to 22 g kg^{-1} is the critical value for the transition from net immobilization to net mineralization. Not all organic materials with high N values, however, exhibit net N mineralization. Lignin contents >150 g kg^{-1} slow N release considerably, and polyphenol contents >30 to 40 g kg^{-1} can result in net immobilization of N (Palm, 1995). Lignin and polyphenols are particularly important modifiers of N release for the fresh, nonsenescent leaves of high-quality materials (Constantinides & Fownes, 1994). The immobilization resulting from polyphenolics, particularly condensed tannins, may be much longer than the temporary immobilization resulting from high C-to-N ratios in cereal crop residues (Giller et al., 1997, this publication).

Net P mineralization patterns are determined primarily by P concentration in the tissue. Materials with P content <2.5 g kg^{-1} immobilize P (Blair & Boland, 1978; Kwabiah, 1997). Phosphorus release patterns are not necessarily correlated to N release. Some materials showing net N mineralization can result in net P immobilization and vice versa (Kwabiah, 1997, personal communication), stressing the importance of looking at more than N in organic materials.

Traditional organic resources, primarily cereal crop residues and cattle manures, fall below the critical N content and immobilize N, at least temporarily. Tanner and Mugwira (1984) found that manures with N content <10 g kg^{-1} caused a decrease in the growth of maize seedlings for 4 wk that was related to immobilization. The negative effect of cereal residues on crop growth has been demonstrated in many field and pot trials (Ishuza, 1987; Nandwa, 1995). On an Alfisol in central Kenya, incorporation of maize stover reduced maize grain yields by 3 to 30% in the first three seasons. After the third year the reduction did not occur (Qureshi, 1987; Nandwa, 1995). Ishuza (1987) reported that incorporation of 2.5 and 5.0 t ha^{-1} of stover resulted in 30 to 60% decreases in soil-available N.

Even if crop residues and other low-quality organic materials can be obtained in sufficient quantities, net N and probably P immobilization will occur, exacerbating the nutrient deficiencies, at least temporarily. The negative effects can be offset by combining with inorganic N (Msumali & Racz, 1978; Ganry et al., 1978; Paustian et al., 1992) or high-quality organic materials with N content >20 g kg^{-1} and P >3 g kg^{-1} (Smith et al., 1993). There are no guidelines as to the amounts of inorganics or high-quality materials needed to offset these negative effects, although as much as 100 kg N ha^{-1} of fertilizer N was needed to overcome the immobilization resulting from mulching with maize stover in Guatemala (S. Waddington, 1997, personal communication).

Although there is some degree of predictive capacity relating nutrient release patterns to organic resource quality, there has been little attempt to relate organic resource quality to fertilizer equivalency values. Frequent claims state that green manures have fertilizer equivalency values of 50 to 100 kg N ha^{-1} (Meelu & Morris, 1985; Ladha et al., 1988; Giller et al., 1997, this publication), but many trials do not provide sufficient information to allow relating the fertilizer equivalency to the quality of the organic materials. Often there is no information given on the amount of the green manure added, its nutrient content, or its C constituents. Indeed as pointed out by Bouldin (1988), the green manure might be a replacement for a limiting nutrient, usually N, and in such cases a fertilizer equivalency value is useful. On the other hand, the green manure may have additional nutrient or physical factors that influence the uptake and use efficiencies (Van Noordwijk & van de Geijn, 1996) and cannot be explained by the addition of N. In such cases, the fertilizer equivalency value is not very useful.

Sources of Carbon and Energy for Soil Organisms

Soil microbes can serve as sources and sinks of nutrients, and their activity and turnover resulting from the decomposition of organic materials are considered to be primary controlling factors in nutrient cycling and availability (Duxbury et al., 1989; Smith et al., 1993). Additions of organic residues can increase microbial pool sizes and activity, C and N mineralization rates, and enzyme activities (Smith et al, 1993), all factors that affect nutrient cycling. Since C is often the element most limiting to microbial growth and activity in, soils, the amount and metabolic activity, or C quality, of organic additions will influence rates of nutrient cycling.. Reinertsen et al. (1984) found that the size of the microbial biomass and rate of decomposition of wheat *(Triticum aestivum* L.) straw were determined by the size of the soluble C fraction of the organic materials.

Additions of soluble forms of C also can result in the decomposition of more recalcitrant plant components and SOM, the so-called priming effect. Collins et al. (1990) found that the decomposition of mixes of wheat residues was greater than predicted when parts with more soluble C were added. Vanlauwe et al. f1994) also confirmed that more soluble C fractions in plant materials enhanced the decomposition of the more recalcitrant fractions. Other nutrients, particularly N and P, also are probably mineralized by the priming effect of soluble C, but the topic remains controversial (Azam et al., 1993).

Organic additions to soil also can cause a shift in the distribution of nutrients in the organic or inorganic soil fractions caused by microbial activity. This redistribution might affect nutrient availability patterns and nutrient use efficiency, the net effect depending on the quality of the organic addition. As an example, Chauhan et al. (1981) and Hedley et al. (1982) measured changes in soil P fractions following addition of cellulose and N, plus or minus P. They concluded that for long-term build-up of soil P, it is necessary to add both a C and a P source. Carbon provides substrate for microbial growth, and subsequent microbial turnover results in the long-term accumulation of organic P, especially the more available P fractions. The same result may apply if a low-quality organic with low nutrient content but high amounts of available C was applied and resulted in net immobilization of the inorganic P. If higher proportions of N are held in soil organic fractions, they would be less susceptible to gaseous losses and leaching. On the other hand, additions of a high-quality material, with high nutrient content and high amounts of available C, may simply result in the substitution of the organic and inorganic sources of the nutrient (Jenkinson et al., 1985).

In summary, C inputs, particularly the soluble fractions, modify the rate at which nutrients are cycled and become available and the form in which nutrients are held in the soil. This has not yet been translated into a clear framework for practical management, such as the amounts of different quality materials required to prime the system, or the proportions of organics (of different quality) to inorganics that would result in greater efficiency in the use of nutrients by reducing nutrient losses.

Precursors to Soil Organic Matter

It is through the formation of SOM that organic materials show longer term residual effects than do inorganic fertilizers. The use of inorganic fertilizers alone can even lead to a decline in SOM, while fertilizers combined with organics or organics used alone can maintain SOM levels (Sharpley, 1985; Bationo et al., 1995). The relative roles of the quantity or quality of organic inputs in maintaining SOM, however, are not well understood. Many experiments include applications of organic materials of different quality, but they also are applied in different quantities, making it difficult to interpret results. Even when similar amounts of different quality organic inputs are applied, some studies have shown that materials with higher C-to-N ratios and higher lignin contents result in more SOM (Janzen et al., 1988; Paustian et al., 1992), while others have shown no effect of organic input quality (Larson et al., 1972).

Simply maintaining or increasing SOM may not necessarily lead to increased nutrient availability or productivity. Research in the past decade has focused on separating SOM into different fractions that are related to functional properties (Parton et al., 1989; Stevenson & Elliott, 1989), and particularly into a biologically meaningful fraction that is related to) nutrient-supplying capacity (Magid et al., 1996). Certain fractions, such as rtiicrobial biomass and the light fraction, have been positively correlated with N mineralization or N availability (Bonde et al., 1988; Hassink, 1995; Barrios et al., 1996). It is not yet clear how the quality of the organic input affects the different SOM fractions. Barrios et al. (1997) found that the amounts of light fraction under managed fallows of trees were higher for trees with low (lignin + polyphenol)-to-N ratios in litter than for trees with higher ratios in litter, although these results have been confounded with different amount of organic additions in the different treatments.

Kapkiyai (1996) found in Kenya that additions of farmyard manure (FYM) over 18 yr increased the content and relative proportions of soil microbial biomass and particulate organic matter compared with additions of maize stover, though the amounts of FYM added also were much larger than those of maize stover. These more labile soil organic fractions were correlated to higher crop yields.

Organic amendments may increase SOM, depending on the amounts and quality of me materials added. Few experiments have controlled for the separate effects of the amount and the quality of the organic material and have included measurements of the resulting SOM fractions. Such experiments and measurements are necessary to identify possible relationships between organic inputs, SOM content and composition, and crop production. This information also is needed to determine how different types of organic materials produce residual effects in terms of a nutrient substitution value.

Competitors **for** Phosphorus-Sorption Sites

Organic materials have been shown to reduce the P-sorption capacity of the soil and increase P availability. The magnitude and duration of the effect varies with the soil type, the quality of the organic material, and the amounts added (Singh & Jones, 1976; Sivapalan & Sivasubramaniam, 1979; Bumaya & Naylor, 1988; Iyamuremye et al., 1996a). In general, only materials with >2.5 g P kg^{-1} have been shown to reduce the P-sorption capacity (Singh & Jones, 1976).

The mechanisms involved in this process are quite complex, as outlined in a recent review by Iyamuremye and Dick (1996). The most commonly cited mechanism refers to me action of organic acids produced from decomposition or root exudation. It is variously proposed that me organic anions (i) complex (or chelate) with ions of Fe and Al in me soil solution, preventing the precipitation of phosphate, and also reducing Al and Fe toxicity, (ii) compete with P for sorption sites, and/or (iii) solubilize P from me insoluble Ca, Fe, and Al phosphates. Work by Hue (1991), Violante and Gianfreda (1993), and Staunton and Leprince (1996) indicate that complexation and competition are more important than replacing sorbed P or solubilizing native P.

The most effective organic anions are the di- and tri-carboxylic acids such as tricarboxylic citric acid and me dicarboxylic malic, tartaric and oxalic acids, whereas monovalent acetate was found to have little effect (Hue, 1991; Iyamuremye & Dick, 1996; Staunton & Leprince, 1996). There is a question if organic acids can be found in the soil in sufficient quantities and for sufficient time to have such an effect on P availability. Levels of organic acids mat Hue (1991) and Staunton and Leprince (1996) added were similar to those found in soils. Although Staunton and Leprince (1996) report that these levels may not apply to me bulk soil, such levels may be found in the rhizosphere from root exudation. Iyamuremye et al. (1996b) found increased levels of malic, malonic, uccinic, formic, and acetic acid in soil following additions of manure, although the levels they added were quite high, >50 t ha^{-1}.

It is important to realize that most of the experiments showing reduction in P sorption with additions of organic materials have been conducted in the laboratory at unrealistically high loading rates. Another factor that has not be addressed adequately is the C quality of the organic materials and how it affects the production of different organic acids during decomposition. The practical issue then becomes, can organic inputs decrease P sorption and increase P availability in the field under farmer circumstances at currently available types and rates of organic inputs?

Indirect Effects on Nutrient Acquisition

Organic materials also can have several other effects on soils and plants that influence nutrient acquisition and uptake by plants. Root growth can increase as a result of reduced exchangeable Al in the soil, caused by complexation with organic anions that are produced by me decomposition of organic materials (Hansen, 1989). It also can increase though an increase in pH caused by the addition of basic cations from organic materials (Kretzschmar et al., 1991). Organic materials also can stimulate root growth either directly or through their effect on soil bacteria that can suppress root pathogens and produce plant growth hormones (Marschner, 1995). It is important to note that organics also can inhibit root growth, particularly if phenolics concentrate in the soil or if bacteria detrimental to root growth increase because of the addition of organic materials.

Applications of organic materials also can reduce or increase the numbers of pests and weeds, again depending on the quality of the material. Mulching with low-quality materials that decompose slowly has been shown to decrease weed biomass, while high-quality materials that decompose quickly have little effect (Fernandes et al., 1993; Salazar et al., 1993). The increased soil-water content resulting from mulch cover can, however, increase the incidence of pests. There is some evidence that the parasitic weed *Striga* sp. that reduces maize yields in much of Africa can be curtailed by applications of organic materials (Ransom, 1996). The decrease is probably caused by several factors, including increased soil-water content, higher soil-available N levels, and perhaps even the suicidal germination of striga seeds caused by the products of organic decomposition (Vogt et al., 1991; Ransom, 1996).

Soil physical properties such as structure, water content, and temperature can be affected by incorporation or surface application of organic materials. As an example, Tian et al. (1993) found that during drier periods lower quality mulches resulted in higher yields, as mineralization was probably higher because of the more favorable microclimate, lower soil temperatures, and higher soil-water content produced by the low-quality mulch.

A summary of the role of organic materials in affecting nutrient availability and crop production brings out several points (Table 8-3). Despite some uncertainties in the role of organic materials, they are not magic. Nutrients from organics, once mineralized, are no different from inorganic nutrients. Many of the functions of organics have been well described and understanding of them has reached a predictive stage. Now is the time to incorporate this predictive understanding into the management of organic materials for soil fertility improvement.

Table 8-3. Summary of the various roles of organic materials in affecting nutrient availability and acquisition.

Factors affecting nutrient availability	Summary points
1. Nutrients added	• Insufficient quantity and quality of traditional organic sources to meet crop demand • Most materials recycle nutrients rather than add them to the system
2. Mineralization patterns	• Immediate net N release if material has >18 to 22 g N kg^{-1} • Lignin content >150 g kg^{-1} reduces N mineralization rates • Soluble polyphenol contents >40 g kg^{-1} can result in prolonged net N immobilization • Net P release if material has >2.5 g P kg^{-1}
3. C as energy source	• C is limiting to microbial growth and activity in most soils • C addition can result in conversion of inorganic nutrients to organic forms • Metabolic C primes mineralization of C, N, and P from more recalcitrant fractions
4. Precursors of soil organic matter (SOM)	• Labile fractions of SOM (microbial biomass and light fraction) are correlated to nutrient availability • Relative effects of quantity and quality of organic materials on SOM and labile fractions not certain
5. P sorption	• Organic anions from decomposition or root exudation compete for P-sorption sites • P sorption reduced by materials with P >2.5 g kg^{-1} • Effect of C quality of inputs not certain • Total effect on nutrient availability likely to be small
Factors affecting nutrient acquisition	
6. Root growth	• Al toxicity of soil reduced by organic materials, can result in increased root growth • Organic materials stimulate (inhibit) root growth directly or through effects on microbial populations
7. Weeds	• Low-quality mulches can suppress weed growth • Striga reduced with organic materials through effects on soil N or early germination of striga seeds

COMBINING ORGANIC AND INORGANIC NUTRIENT SOURCES

The role of organics is varied and complex, as detailed above; the challenge is to use organics of differing quality in combination with inorganic fertilizers to optimize nutrient availability to plants. This requires knowing how the nutrient content and C quality of organic materials will add to and compensate for or will reduce nutrient availability from inorganic fertilizers. The term *interaction* is frequently used to describe the net effects of the combined use of organic and inorganic sources. This term implies to some a magic effect of organic materials, whereas to others it merely means a statistical interaction. A better phrase than interactions might be added benefits (or disadvantages) resulting from the combined use of organic and inorganic inputs compared with inorganics alone. In general, the nutrients supplied or removed (immobilized) by the addition of organics are additive to those supplied by inorganic nutrient sources (Paustian et al., 1992; Jones et al., 1996; Giller et al., 1997, this publication). Added benefits, or disadvantages, of combined nutrient additions are probably more related to the quality of the C substrate of the organic material and its effects on nutrient availability.

Unfortunately, there has been little synthesis of the integrated effects of organic materials on net nutrient availability that can provide guidelines for combined nutrient management. An examination of past field trials and soil-crop simulation models, where the processes are integrated, may provide a starting point for assessing the relative importance of the various effects with different qualities of organic materials.

The original intent of this chapter was to review and synthesize information from the numerous trials that have been conducted using combinations of organic and inorganic nutrient sources. It quickly became apparent that most trials did not permit interpretation and extrapolation that would lead to management guidelines because of their experimental designs.

Numerous trials have compared the yields from a given amount of inorganic fertilizer *(A),* an organic material *(B),* and their combination *(A + B),* and in many situations *(A + B)* produced higher yields than *A* or *B* alone. It should not be surprising that the combination does better because more total nutrients have been added than in *A* or *B* alone. Nutrients from the organic sources are considered in a additive manner *(IA + IB)* to that of the inorganic source, rather than looking at the substitution value *(xA + yB,* where the sum of *x* and *y* equals 1). Critical information on the nutrient content and quality of the organic material is often not provided. Despite some design flaws, a number of observations can be made regarding the combination of organic inputs of varying qualities and inorganic fertilizers on crop yields and nutrient-use efficiency.

Synchrony of Nutrient Availability and Crop Demand

A 4-yr experiment in India (Goyal et al., 1992) compared the N substitutive effects of wheat straw, FYM, and sesbania (species not given) green manure on pearl millet *[Pennisetum glaucum* (L.) R. Br.] yields, N uptake, and SOM. Nitrogen was applied to pearl millet at a rate of 120 kg N ha^{-1}, as urea alone or one-half applied as urea and one-half applied as wheat straw, FYM, or sesbania. Data were presented for only the fourth year of the experiment (Table 8-4). Crop yields, N uptake, and N recovery were greater with the combination of FYM or green manure and urea compared with urea alone but less when wheat straw was combined with urea. The decrease in yields with wheat straw even after 4 yr is related to net N immobilization that would be expected from a material with a C-to-N ratio of 102. The authors attributed the higher N use in the combined sesbania or FYM with urea to the immediate availability of N from urea and its delayed release from the organics, achieving greater synchrony with crop demand.

Another trial in India compared the N substitutive effect of organics by adding 80 kg N in various proportions of leucaena *[Leucaena leucocephala* (Lam.) de Wit] and urea, with 100, 50, 25, or 0% of the N added as leucaena and the remainder added as urea (Mittal, 1992). Applications were made annually for 3 yr. Maize yields obtained from the 100% leucaena and 100% urea treatments

Table 8-4. Pearl millet yield, N uptake, N recovery, and soil properties following 4 yr of application of fertilizer (urea) compared with the combination with organic materials of differing qualities (adapted from Goyal et al., 1992).

Treatment!	Grain yield	N uptake	N recovery	SOM-Ct	Microbial C
	tha-[1]	kg ha-[1]	%	gkg-[1]	mg C kg-[1]
NOPO	1.51	31	—	4.0	180
N120 P40	2.76	66	29	4.3	290
N60 P20 + N60 (FYM)	2.81	71	33	5.0	330
N60 P20 + N60 (wheat straw)	2.33	51	17	4.5	355
N60 P20 + N60 (sesbania)	3.15	76	38	4.8	315
LSD *(P* = 0.05)	0.27	5.7		0.6	19

t N = kg of N added as fertilizer or organic material, P = kg of P added as inorganic fertilizer.

were similar the first 2 yr. Yields were slightly higher in the leucaena plots the third year. Yields from the 25% leucaena-75% urea combination were higher than the 100% urea or 100% leucaena treatments all 3 yr.

Jones et al. (1997) compared maize yields and N-use efficiency in Malawi from applications of leucaena or gliricidia *[Gliricidia sepium* (Jacq.) Walp.] residues containing similar amounts of N. Residues were applied with or without inorganic N, but they were not compared with inorganic N applied alone. Yields and N use were higher for gliricidia residues than for leucaena residues. Gliricidia residues result in a large and rapid net N mineralization. Leucaena residues, with higher polyphenol content, exhibit initial net immobilization followed by net mineralization (Palm & Sanchez, 1991; Tian et al., 1992), the total N released by leucaena being less. Additions of inorganic N with the residues produced an increase in yields and N-use efficiency with leucaena but not with gliricidia. Jones et al. (1997) attribute the higher yields obtained from gliricidia to better synchrony of nutrient availability to crop demand. Addition of inorganic N to leucaena improves synchrony by increasing the N supply at the initial stages of net immobilization resulting from applications of leucaena. Although this interpretation is not necessarily incorrect, it is somewhat incomplete because yields from the sole application of equivalent amounts of inorganic N were not included for comparison, as was done by Goyal et al. (1992).

Fertilizer N is subject to gaseous losses and leaching; losses of 20 to 40% are often reported (Van der Kruijs et al., 1988; Christianson et al., 1990). It is commonly believed that combining organics with inorganic fertilizer will increase synchrony and reduce losses by converting inorganic N into organic forms. Studies have generally looked at organic inputs of lower quality, such as crop residues. There are trade-offs between possible reductions in yields from the use of organic materials and greater potential nutrient losses with the use of inorganic nutrients alone. Is it possible that high-quality organic materials can reduce losses of inorganic N without reducing yields considerably?

Janzen and Schaalje (1992) found that fertilizer N losses were twice as large when green manure plus fertilizer was applied to barley *(Hordeum vulgare*

Table 8-5. Dry weights of 2-mo-old maize plants grown in pots treated with equal amount of N, P, and K added as the green manure of *Tithonia diversifolia* or as inorganic nutrients.f

Treatment	Nutrient added N	P	K	Weight of maize
	.	.	i	g pot^{-1}
Control	0	0	0	1.09
Tithonia leaves	170	14	230	6.04
N-P-K fertilizer	170	14	230	4.58
Tithonia leaves + inorganic P	170	39	230	10.30
N-P-K fertilizer + P	170	39	230	6.23
LSD (P = 0.05)				1.02

t Source, Gachengo, 1996.

L.). Their interpretation was that green manure promoted high levels of nitrate and available C in the soil, enhancing denitrification. Losses were reduced with smaller repeated applications of green manure, again implying that the use of high-quality green manures as partial substitution for inorganic fertilizer N rather that addition to inorganic fertilizer may increase nutrient-use efficiency. Xu et al. (1993a,b) found large losses of 25 to 41% of N added from leucaena prunings. They attribute this to denitrification. Losses are greater when materials are incorporated rather than surface applied (Xu et al., 1993b; Jones et al., 1997). Although these studies did not compare the losses from fertilizer alone, they do indicate that losses from high-quality organics alone can be quite high. Ganry et al. (1978) also concluded that large applications of low-quality straw can result in large losses of fertilizer N through denitrification. These studies indicate that N losses can be quite large from both organic and inorganic sources, contrary to the popular belief that application of organic sources will result in fewer losses.

Reduced Phosphorus Sorption

Application of a high-quality organic material, tithonia *[Tithonia diversifolia* (Hemsley) A. Gray] leaves, combined with inorganic P in a pot trial resulted in greater maize biomass and P uptake than from equal amounts of nutrients added from inorganic fertilizers (Gachengo, 1996). The statistical analysis indicated a significant added benefit of the organic-inorganic treatment compared to the inorganic treatment (Table 8-5). A subsequent field study showed that tithonia application reduced P sorption in the soil up to 16 wk (Nziguheba et al., 1998) and might account for the increased plant growth and uptake of P from the combined nutrient sources.

Soil Organic Matter and Residual Effects

In the study by Goyal et al. (1992) described above, the higher yield produced by the sesbania plus urea and FYM plus urea compared with urea applications alone also could reflect a residual effect after 4 yr of applying the organic materials. They found no differences in total soil C in plots receiving organic inputs compared with fertilizer alone following four annual additions of 2.7, 3.8, and 12 t ha^{-1} of sesbania, FYM, or wheat straw, respectively. Organic treatments did have higher levels of soil microbial biomass C and N, but yield differences from the different organic treatments (Table 8-4) were not related to the soil microbial biomass. The wheat straw plus fertilizer treatment had higher microbial C, relating more to the higher C input from wheat straw than to the quality of the inputs. This treatment also had the lowest yields.

Increased Root Growth

The effects of millet straw residue and/or inorganic fertilizer (N-P-K) on nutrient uptake, soil nutrients, exchangeable Al, and root growth were examined in Niger (Hafner et al., 1993). Higher P uptake rates in the millet residue plus fertilizer treatments was attributed to higher root-length density. This greater root growth could be a result of a reduction in exchangeable Al in the soil, or stimulation of root growth from the organic materials, or both. In an earlier study, the same research group found an increase in base saturation and pH and a decrease in labile Al with additions of millet straw (Kretzschmar et al., 1991) because of the addition of basic cations with the crop residue. The reduction of Al also might be partially due to chelation of Al by organic anions produced by the decomposing straw. The decrease in exchangeable Al was accompanied by an increase in extractable P. Large increases in N_2-fixing bacteria and total bacteria also were found in treatments with crop residues. As noted earlier, bacteria, particularly N_2-fixing bacteria, have been shown to stimulate root production (Marschner, 1995).

Results from these few trials indicate added benefits, and disadvantages, from the combination of organic and inorganic nutrient sources. While synchrony, nutrient-use efficiency, and residual effects of SOM are related to the addition of organic materials, N losses are not necessarily reduced. These added effects of combining nutrient sources are summarized in Table 8-6. The challenge now is to attain a predictive capacity that integrates these processes and the influence of climate, soil, and organic input quality on these processes.

SIMULATION MODELS

Integrating the numerous and complex roles of organic materials in soil fertility and crop growth might be assisted by simulation models. Models, however, are only as good as the data that are used for constructing them, and knowledge gaps still exist on the role of organic materials of different qualities and their interactions with inorganic fertilizers in modifying soil nutrient availability. More controlled experiments are needed that can be used for developing and validating models. Once these models exist, they can assist in evaluating organic-inorganic combinations and in selecting and optimizing combinations.

Models that can be used for investigating the combined effects of organic and inorganic inputs must have the capacity for (i) additions of organic inputs of differing quality, with decomposition routines that include organic quality parameters, (ii) links between organic quality and the formation of different SOM

Table 8-6. Potential added benefits or disadvantages, resulting from the combined application of organic and inorganic nutrient sources, compared with inorganic nutrient sources applied alone.

Potential benefit or disadvantage of combined nutrient sources	Relative impact+
1. Organic materials provide additional nutrients that may be colimiting to plant growth	++
2. Organic materials alter nutrient availability patterns	
A. High-quality materials (low C/N ratio, low lignin, low polyphenol) produce somewhat delayed N availability patterns, when coupled with inorganic fertilizer may increase supply-demand synchrony	+
B. Medium-quality materials (low C/N ratio, low lignin, high polyphenol), may decrease N availability over the short- and medium-term if polyphenols have high protein-binding capacity but may result in greater residual effect in the longer term	-/+ depending on time
C. Low-quality materials (high C/N ratio, high available C) result in immobilization of added fertilizers	
D. Low-quality materials (high lignin) may decompose faster when combined with inorganic N	+
3. Available C from organics primes the mineralization of N and P from soil organic matter, adding to the available nutrients	0
4. Organic materials reduce P sorption by mineral soil, making added inorganic P more available	0 to ++, depending on soil type
5. Organic materials build up soil organic N and P in the longer term and through repeated applications can partially substitute for inorganic additions	++
6. Organics increase root growth so plants are better able to exploit fertilizer	+
7. Organics reduce weed populations and reduce competition for added fertilizers	++

t + = added benefit, - = disadvantage, 0 = neutral or small impact; the number of + or - indicates relative impact.

fractions, (iii) crop production models that are sensitive to short-term changes in nutrient availability, and (iv) both N and P dynamics, which in the case of P must include P sorption as affected by organic materials. The strengths and weakness of the various models that currently exist are reviewed below.

Models vary considerably in their ability to handle different quality organic inputs. The CERES models include decomposition and N dynamics of cereal and legume residues, with decomposition determined by the C-to-N ratio of the organic material (Dimes, 1996). In the CENTURY model, decomposition and N mineralization are driven primarily by the lignin-to-N ratio of the material (Parton et al., 1989). Recently, Whitmore and Handayanto (1997) included the effect of polyphenolics and their protein-binding capacity on N dynamics and availability, which is particularly important for systems that include legumes.

Models of P in soil-plant systems initially were physicochemically based, with organics and P cycling ignored. Currently, models such as EPIC (Jones et al., 1991) and CENTURY include organic P components. The CENTURY submodel divides P into several pools, both organic and inorganic, with a primary P pool (assumed to be apatite), secondary, occluded and labile mineral P pools. Recent users of the CENTURY model have been rather critical of the P submodel for tropical soils (Gijsman et al., 1996). None of the models adequately deal with P sorption and the effects of organic additions.

The strengths of the CENTURY model are its ability to predict long-term changes in SOM; however, it does not simulate short-term nutrient availability and crop production well because of the month-long time step (Paustian et al., 1992). Cropping systems models, such as APSIM (McCown et al., 1996) and DSSAT (Tusji et al., 1994), simulate short-term crop production but are limited in their ability to model decomposition and SOM dynamics. Thus far, there seem to have been no attempts to merge the detailed soil process models with the crop models that are better at simulating crop growth and yield. Van Noordwijk and Van de Gejin (1996) also stress that models mat include root processes are essential for simulating nutrient dynamics.

Myers (1995) used CENTURY to simulate a 15-yr experiment conducted in Thailand in which a range of organic materials was applied in the presence and absence of N fertilizer. The model successfully provided a qualitative description of the changes in SOM but underestimated SOM accumulation in soil, particularly in plots that received fertilizer and crop residues. Paustian et al. (1992) reported similar discrepancies. The model also underestimated SOM in plots that received the largest amounts of organic inputs. Aboveground crop production was simulated well in only about one-half the cases and corresponded to cases where SOM was simulated well.

In the opinion of these authors, current simulation models do not yet fully meet the needs of research and extension workers in developing countries. The major issues that need attention, assuming that the suite of crop models is adequate, are the capacity to simulate P dynamics and the decomposition of a broader range of crop residues and higher quality organics that are likely to be encountered in tropical farming systems. Development of models that can be used in such situations for selecting appropriate mixes of organic and inorganic inputs will require closer interaction between the modelers and the experimentalists.

A FRAMEWORK FOR INVESTIGATING THE COMBINED USE OF ORGANIC AND INORGANIC INPUTS

The capacity to make practical recommendations on the use of organic materials as a source of nutrients for crops will be limited until the different factors that affect yields are separated and accounted for through appropriate trials and the organic resources are sufficiently characterized. This is a complex task. To advance from the current empirical status to a predictive capacity for the selection and management of combined organic and inorganic inputs, a few knowledge gaps must be filled, which requires appropriate hypotheses and experimental designs. A systematic framework is proposed for the investigation of combined organic and inorganic inputs (Fig. 8-1).

An initial step is to conduct surveys that include interviews and visual assessment of the farm vicinity and community, on the availability and quantities of organic materials and fertilizer. Emphasis should be placed on alternative, high-quality materials that exist in the landscape or for niches to plant nonfood crop legumes. The surveys should also assess the farmers' current soil fertility management practices, constraints, and opportunities. The soils of the area also

On-farm and community assessment

- Soil types and corresponding limiting nutrients
- Availability and types of inorganic fertilizers
- Availability and amounts of organic inputs
- Potential niches for planting non-food legumes

Characterization of organic inputs

- Nutrient concentrations
- Carbon quality

Establishment of fertilizer equivalency values

- Laboratory incubations
- Field trials
- Multiple nutrient effects
- Relationship to organic input quality

Combination of organic **and** inorganic nutrients

- Based on fertilizer equivalency values
- Factorial trials
- Optimization trials
- Long-term and residual effects
- Economic analysis

Fig. 8-1. A systematic framework for investigating the combined use of organic and inorganic nutrient sources, in relation to farmer circumstances, organic resource quality, and their nutrient substitution values.

must be characterized in terms of the primary limiting nutrients. This can be done by soil tests or limiting nutrient trials.

Organic materials that have been identified should then be characterized for their quality parameters. The minimum of parameters that should be included are macronutrient concentrations, lignin, soluble C, ash, and soluble polyphenols (if the N concentration is >18 g kg^{-1}). Standardized methods for these analyses are also recommended (Palm & Rowland, 1997). Once a sufficient number of materials of the same species have been characterized to indicate the possible range in quality within a species, it might be possible to categorize a plant material into a specific quality grouping without analyzing the material.

Fertilizer equivalency or nutrient substitution values of organic materials can then be determined and related to the quality of the material. Such information could be obtained through a combination of laboratory incubations and field trials. Incubations establish the amount of different organic materials needed to attain similar soil available nutrient levels for a given amount of fertilizer. Field trials test recommendations from the incubations on different soils and climates, and models extrapolate to other types of organic materials and environments.

Field trials usually relate the yield obtained from organic inputs to the yields obtained from an inorganic response curve. One must be certain of the limiting or colimiting nutrients of a particular soil and then decide if the trial will assess the nutrient equivalency of one or multiple nutrients. If only one nutrient is to be assessed then the other nutrients must be supplied in nonlimiting quantities in the inorganic response curve and the organic treatments. If multiple nutrients are to be assessed, additional multiple nutrient response curves must be included. Rates of nutrients applied from the organic sources must be on the responsive part of the fertilizer response curves; if not, then the trials will not be useful.

The outcome of these types of trials will permit grouping of organic materials into like categories, based on their quality, that have similar nutrient substitution capacities per unit of added material. As an example, the recommendation might say that for materials with N content of 40 g kg^{-1}, lignin content <50 g kg^{-1}, and polyphenol <30 g kg^{-1}, then 4 t of material is needed to produce an N equivalency of 80 kg N. This type of material containing 160 kg N would have an N-application efficiency 50% that of the fertilizer. These recommendations would, of course, differ with soil, climate, and crop.

Once fertilizer equivalency values have been established for different groups of plant materials, trials can determine the substitutive effect of different quality organics at different proportions of organic-to-inorganic sources. These trials could be factorial with several rates of both the organic and the inorganic materials or substitutive in which the organic and inorganic inputs are added at different proportions but the total amount of nutrient added is the same (Mittal et al., 1992). Both types of trials have merit.

A factorial arrangement of treatments provides a means for comparing different rates but has the limitation that most of the combined treatments are additive rather than substitutive in nature. The number of treatments quickly becomes prohibitive if more than one organic material is assessed, in which case confounded designs can be used (Jones, 1996). For assessing low-quality materials, perhaps only one rate that is normally used by farmers should be used with several rates of the inorganic to determine how much inorganic fertilizer is needed to overcome the negative effect of the low-quality organic.

The other design, in which the total amount of nutrients added is the same but the proportion of organic-to-inorganic source changes, is useful to determine the optimal combinations in terms of economics, nutrient-use efficiency, and residual effects. This design will indicate if the two nutrient sources are merely substitutes *(Q1)* or if there is some additional benefit *(Q3)* or disadvantage *(Q2)* to be derived from the organic material (Fig. 8-2). Economic analyses of the various organic-inorganic combinations should be conducted under current conditions and future scenarios, to indicate realistic management options.

These trials should be planned for the long term to assess residual effects and changes in SOM composition as they relate to the quality of the organic material and the proportion of organic to inorganic. Until such trials are conducted that link the quality of the organic material to its fertilizer equivalency value and its effect on the longer term composition of SOM and crop yields, there will be no means of providing guidelines for the combination and efficient use of organic and inorganic inputs.

The desired outcome of the research process detailed above is to acquire fairly simple tools that can be used by researchers, extensionists, and farmers for assessing different ways of using scarce resources for maintaining soil fertility

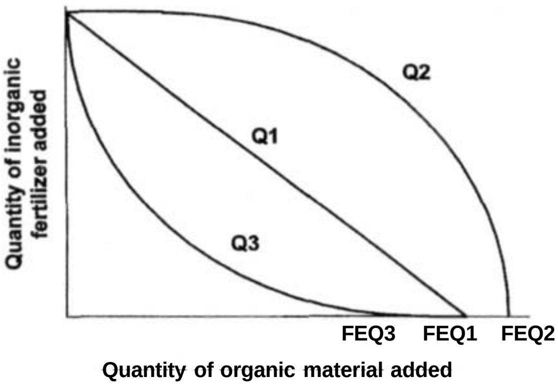

Fig. 8-2. A conceptual model depicting the amounts and proportions of organic materials of differing quality (Ql, Q2, Q3) and inorganic fertilizers necessary to achieve a desired yield. All lines represent the same yield. FEQl, FEQ2, and FEQ3 represent the amount of each of the respective organic materials (Ql, Q2, Q3) needed to achieve the same fertilizer equivalency value.

and improving crop yields. An example of one such tool is a preliminary decision tree on the uses of organic material of different qualities for N management (Fig. 8-3). The decision tree is a current best bet based on research results. It can be modified as more information becomes available, but more importantly it can be implemented with farmers and modified based on their experiences and available resources.

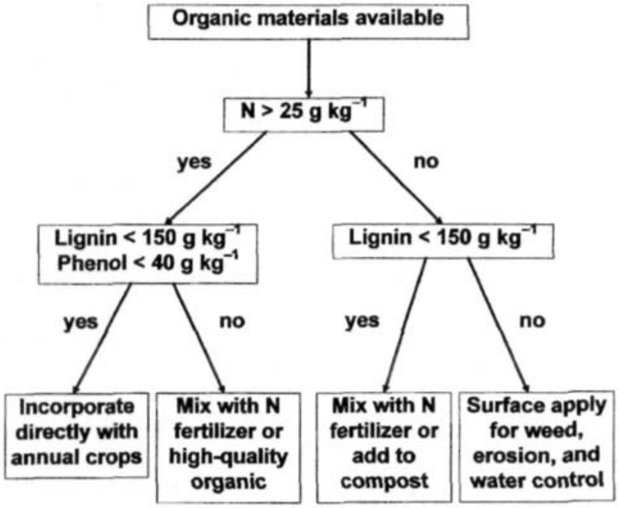

Fig. 8-3. A preliminary decision tree that can be used and modified by researchers, extensionists, and farmers for managing organic resources and inorganic fertilizers.

CONCLUSIONS

Many farmers in Africa, and their colleagues worldwide, are currently combining organic and inorganic sources of nutrients to try to meet crop demands. Yields obtained are far below their potential because of inadequate amounts added, the low quality of the organic materials, and inappropriate or inefficient combinations. Given the high cost and uncertain accessibility of inorganic fertilizers in Africa, the goal should be to provide much of the nutrients through organic inputs, making up the shortfall of the limiting nutrients through inorganic fertilizers. Where the quantity and quality of organic materials is low, there is a need to find alternative, high-quality organic materials that can be incorporated in the current farming systems.

Despite numerous field trials combining organic and inorganic inputs, it is not at present possible to recommend guidelines for combining organic and inorganic nutrients because of inadequate experimental design and little information on the quality of organic inputs. Inorganic fertilizers can offset the negative effects of low-quality organics but how much cannot be specified. Higher quality organic materials can substitute for inorganic fertilizers, but there are no prescriptive guidelines that relate the quality of the organic material to its nutrient substitution value.

Prescriptive guidelines can be attained once links are made between the quality of the organic materials and their short-term fertilizer equivalency value and longer term residual effects through SOM formation. These guidelines also must incorporate farmer perceptions and circumstances, including available resources, resource allocation, farm niches, soil types, and limiting nutrients.

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9 Gender and Soil Fertility in Africa

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ABSTRACT

Population pressures, currency devaluations, and fertilizer subsidy removal programs in many African countries have caused renewed concern about soil degradation and loss of soil fertility. Advances in food production are further constrained by the *invisibility factor,* i.e., women do most of the food farming in sub-Saharan Africa, but have little access to the means necessary to significantly increase output and yields. We call this the *invisibility factor* because agricultural experts commonly do not acknowledge that most of Africa's smallholders are women, and women's yields, women's adoption, and women's use of inputs are rarely reported. Gendered differences in wealth result in women's lowered access to cash and credit, needed to acquire both organic and inorganic fertilizers. The solution to this problem, we believe, lies in better collection of gender-desegregated data as well as better programs and policies that take into consideration the severe cash constraints women farmers face and that target women farmers with crucial inputs of production such as fertilizers. Because women lack cash, we recommend as a general objective achieving low application rates of about 25 kg nutrient ha"^{1}, depending upon soil and climatic conditions. Options proposed to target women farmers with greater fertilizer inputs include fertilizer vouchers, providing fertilizer in small bags in local markets, microcredit, free grants of fertilizer, use of organic materials, biological N_2 fixation technologies, combinations of organic and inorganic fertilizers, and improving women's access to cash-crop markets. As part of USAID's Soils Management Collaborative Research Support Program, we propose to test these different methods in several African contexts from 1997 to 2002.

There is a new sense of urgency about achieving food security for sub-Saharan Africa (hereafter referred to as Africa; Borlaug & Dowswell, 1995). Most African countries still depend on agriculture for most of their gross national product and employment (Tomich et al., 1995). Yet Africa currently imports a large proportion of its food grains, e.g., one-third of its rice *(Oryza sativa* L.) consumption and two-thirds of its wheat consumption (Eicher, 1995). Whether it can continue to do so is questionable. In 1995-1996, world commodity prices of major food crops skyrocketed. Because world stocks of rice, wheat *{Triticum aestivum* L.), maize *(Zea mays* L.), and other grains fell to their lowest levels in 20 yr, the world price of maize jumped from US$ 2.43 to more than US$ 5.00 a bushel; wheat prices also jumped from US$ 3.49 to more than US$ 6.00 in 1995-1996.

Because Africa's population is expected to increase by 100 million during the next 6 to 7 yr, there is intense pressure to increase food supplies from domestic production (Eicher, 1995). Yet after 10 yr of structural adjustment programs that sharply devalued currencies and removed fertilizer subsidies, fertilizer prices are so high that fertilizer use on food crops is now often unaffordable in many African countries (Bumb et al., 1996).

In most of Africa, advances in food production are further constrained by the invisibility factor, i.e., women do most of the food farming but have little access to the means necessary to significantly increase output and yields. On average, African women provide 46% of the labor inputs and are responsible for up to 80% of domestic food production in some societies (Dixon, 1982; Gladwin & McMillan, 1989). We call this the *invisibility factor* because agricultural experts commonly do not acknowledge that most of Africa's smallholders are women, and women's yields, women's adoption, and women's use of inputs are rarely reported. They correctly argue that development strategies need to reach African smallholders to be effective, but they ignore the fact that the constraints facing women smallholders may be an important part of the problem. Eicher (1982, 1995), for example, consistently does not mention that 45% of the smallholders responsible for Zimbabwe's second Green Revolution (1980-1986) are women; nor does he indicate the percentage of hybrid maize that was adopted by women or the percentage of fertilizer subsidies that went to women. Similarly, Smale's (1995) report on Malawi's *delayed* Green Revolution does not indicate women's adoption of hybrid maize; yet women's maize varieties, comprising 95% of total maize production in 1987, are usually unfertilized local varieties consumed at home while men's hybrid varieties are sold as cash crops (Gladwin, 1992).

CAN AFRICAN AGRICULTURE BE TURNED AROUND WITHOUT HELPING WOMEN TO FARM?

The invisibility of women farmers has led to a debate about whether a turnaround in African agriculture can occur without helping women to farm. Most experts conclude that women farmers are essential for increasing Africa's food production, at least in the short run, because there are just too many women farming to ignore them (Dixon, 1982). Dixon's revision of International Labor Organization (ILO) estimates of women's participation in the labor force indicate that women represent on average 46% of the agricultural labor force in Africa when (i) subsistence production is counted as economic activity, (ii) unpaid family helpers are routinely included, (iii) all agricultural work is recorded, (iv) the survey is taken in the peak season, and (v) the definition of agricultural work includes gardening, raising poultry, and transporting crops to market.

In the long run, however, African women farmers may be displaced from farming by men—just as black farmers in the southeastern USA were displaced by white farmers in the 1950s to 1970s (Gladwin & McMillan, 1989; Gladwin 1996). Boserup (1970) suggests that intensification of agricultural production causes women's participation in farming to decrease relative to men's. Female farming systems are prevalent in African societies with low population densities and an ample land-to-person ratio such that families can produce their food with low labor inputs using shifting cultivation. These systems decline with population growth and agricultural intensification and are replaced by male farming systems as the plow is introduced (Boserup, 1970, p. 16-36).

The displacement of women farmers with intensification, however, may be slowed down or mitigated by other location-specific factors (Gladwin & McMillan, 1989). These factors include extensive male outmigration from rural areas to the cities or mines for nonfarm work. In many parts of Kenya, female-managed households with migrant husbands account for 47% on average (Thomas-Slayter & Rocheleau, 1995, p. 14). In western Kenya, men often spend their lives working in the city, returning to the homestead a few times a year and retiring back to the countryside in their elder years. Other factors include the (i) resurgence of rinderpest and trypanosomiasis, which are slowing down the emergence of animal traction and thus the plow (FAO, 1983), and (ii) location-specific soil types (i.e., sandy soils) and terrain (i.e., steep mountain slopes), which may make hand hoes preferable to plows even under permanent cultivation (Pingali et al., 1987). The intensification process and thus the displacement of women farmers is not likely to proceed at the same rate or in the same pattern in all African countries.

Yet women farmers have already been replaced in many parts of rural Africa, because development planning often still fails to include women, and new technology often continues to go only to the men farmers, despite all the concern with women in development (WID; Dey, 1981; Fortmann, 1981; Spring, 1986; Goheen, 1996). Most externally funded development projects are aimed primarily at men because they are run by men. The majority of extension agents are male, with a few exceptions housed in a poorly funded WID office (Staudt, 1975). Men tend to monopolize new capital inputs, whether they are mechanical or biological (e.g., plows or fertilizer), as regression results from data on 137 agricultural societies in the Human Relations Area Files show (Burton & White, 1984). Yet women farmers are interested in new technologies and want development interventions (Due et al., 1983). In addition, numerous studies show that women farmers still lack access to (i) the basic agricultural inputs of land, labor, capital or credit, and organic and mineral fertilizers (hereafter referred to as inorganic fertilizers), (ii) extension advice, and (iii) the market and political arena (Staudt, 1975; Elson, 1989; Due, 1991; Elabor-Idemudia, 1991; Goheen, 1991; Guyer& Idowu, 1991; Saito et al., 1994).

ARE WOMEN FARMERS AS PRODUCTIVE AS MEN FARMERS?

Why haven't women been included in the past? Why has women's access to productive inputs been blocked? One rationale given is that men farmers are more productive than women farmers. It is true that the raw, unanalyzed data on yields of female-headed households (FHHs), which comprise 25 to 35% of African households, compared with those of male- or joint-headed households show that FHHs have less labor and plant smaller crop acreages, have less access to credit and plant more subsistence crops, and are therefore not as productive as men (Due, 1991; Due & Gladwin, 1991). An analysis of productive efficiencies, however, requires the proper estimation of a production function that controls for other explanatory variables besides gender, e.g., the studies of agricultural productivity done by Robert Evenson and his students (Bindlish & Evenson, 1993; Alderman et al., 1995; Quisumbing, 1996). When researchers estimate a production function that controls for other explanatory variables such as input levels (e.g., land, labor, capital, extension advice, and education), most studies show that male and female farmers are equally efficient as farm managers (Moock, 1976; Bindlish & Evenson, 1993; Saito et al., 1994).[1] When these other explanatory variables are held constant while an independent gender variable is allowed to vary in a multiple regression analysis, researchers usually find that the independent gender variable (expressed as a dummy variable or intercept shifter) is not significant (Quisumbing, 1996). What this means is that "the gender yield differential is caused by the difference in the *intensity* with which measured inputs of labor, manure, and fertilizer are applied on plots controlled by men and women rather than by differences in the *efficiency* with which these inputs are used" by men and women (Alderman et al., 1995). Alderman et al. (1995) conclude that household output could be increased by 10 to 20% by reallocating the inputs (e.g., moving some fertilizer) from plots controlled by men to plots controlled by women.

If women were given the same access to yield-increasing inputs as men, then the smallholder agricultural sector would see significant increases in agricultural productivity. African countries that address these gender disparities in input use and remove these barriers to women's productivity would increase their aggregate agricultural productivity.

WOMEN'S ROLES IN THE AFRICAN HOUSEHOLD

Why are women farmers not given the same access to yield-increasing inputs as men? The answer to this question requires an understanding of the special features of me African household. The African household is usually an extended rather than a nuclear family, with individual production and consumption units embedded within it. These units tend to be semi-autonomous and are

[1] A typical form of Cobb-Douglas production function would be estimated by ordinary least squares by taking logarithms on both sides:

$$\text{In } Y = a_0 + a. \text{ In } I + a_2 \text{ In } T + b \text{ In } E + c\, EXT + d\, Gender + e,$$

where Y is output; L is labor input (hired or family); T is a vector of land, capital, and other inputs; E is educational attainment; EXT is an index of extension services; *Gender* is the gender of the household head or farm manager; and e is the error term. The coefficient that indicates gender differences is d, an intercept shifter (Quisumbing, 1996).

often female-headed households headed by women such as the wife or wives (in polygamous societies) of the household head, or his daughters-in-law or sisters-in-law (in societies with substantial male outmigration of adult sons or younger brothers, who would normally live in the same rural compound with the household head). The female-headed households may be *de facto* or *dejure.* A *de facto* female-headed household is one in which the husband is temporarily away, making it necessary for the wife to make at least some of die agricultural decisions and support the family, possibly aided by remittances from the husband. A *dejure* female-headed household is one in which the head is divorced, widowed, or a single parent and must make all decisions and provide all support for the family. The resource base of these two types of female-headed households could potentially be very different, depending on the size and frequency of the remittances. In an additional 14% of African societies (Vaughan 1986), the units may be headed by a woman simply because the society is *matrilineal,* one in which inheritance passes through the mother, or *matrilocal,* one in which children belong to and reside in their mother's, not father's, lineage or family. Autonomy of the unit comes from two sources. First, the woman in each unit has some responsibilities independent from the household head to feed or clothe or educate the children in her unit. Depending on the cultural rules, she may be responsible for certain foods or all the food during a certain period, e.g., the hunger months. Second, she fulfills this responsibility with an income stream she herself generates independently of the household head or her husband.

These separate income streams are a second unique feature of the African household and have been well documented in me literature, e.g., Mossi women who own private fields in Burkina Faso (Gladwin & McMillan, 1989); husbands and wives who lend each other money at rates slightly less than the prevailing market rate; the payment of wages inside households; wives who sell water to husbands in the fields; husbands who sell firewood to wives; and both who sell animals to each other on festive occasions (Koenig, 1980; Guyer, 1981; Okali & Sumberg, 1986). In any of these exchanges, the best interests of me household may not coincide with those of particular members, so that it makes more sense to model me household as a collective firm—rather than a unitary entity—in which a wife's budget is delinked from her husband's, to varying degrees depending on the particular culture, and wives respond to changes in their husbands' allocation decisions solely according to their own needs (Jones, 1983; Alderman et al., 1995).

Usually, separate income streams give some autonomy to the women in the household, but they do not necessarily give power to the women heading up the unit, and this distinction is a third significant feature of the African household. Women are relatively powerless compared with the male household head (Moser, 1989; Kabeer, 1994), who may interrupt women's work in their own fields and demand mat they supply labor to the cooperative fields he manages and from which he receives income (Gladwin & McMillan, 1989). Alternatively, he may demand that the wife goes to the store to buy fertilizer for him, or he may take her fertilizer to use on his fields or crops. Asymmetric power relationships within the African household, therefore, influence women's access to yield-increasing inputs of production as well as the fertility of their soils and the yields of their food crops. The question of who gets access to productive inputs is a political question—the result of a power negotiation—and not just an economic question (Bates, 1983). In a power negotiation, women in asymmetric power relationships often lose out to men with greater power, status, and prestige.

CONSTRAINTS TO WOMEN'S USE OF INORGANIC FERTILIZER

Microlevel research in the 1980s has documented the constraints to women's use of inorganic fertilizers. Data collected in Malawi and Cameroon by Gladwin (1991, 1992) showed that the majority of African women farmers used no inorganic fertilizer because they had neither the cash nor the credit to acquire it. In Malawi, the average female-headed household used 34 kg ha^{-1} of fertilizer—significantly less than the 51 kg ha^{-1} of the male-headed household, and the median use of fertilizer by women was zero. Data collected from 36 households in anglophone and francophone Cameroon in 1989 agreed. Women's average fertilizer use was 30 kg ha^{-1} compared with 52 kg ha^{-1} for men, because two-thirds of the anglophone women farmers used no fertilizer at all.

Are these gender differences because of gender itself or gender differences in wealth? The data from Malawi suggested that the lower resources controlled by women might better explain their lower use of fertilizer, because female-headed households owned only 0.8 ha of land compared with 1.33 ha owned by male-headed households (P = 0.0001; Gladwin, 1992). Regression analysis agreed. With the quantity of fertilizer used by a sample of 498 male- and female-headed households in 1986/87 as the dependent variable, results showed that membership in a credit club and use of manure/compost significantly increase the quantity of fertilizer applied per hectare (P = 0.0001 and 0.01); whereas variables of farm size and lack of cash significantly decrease the quantity of fertilizer applied per hectare (P = 0.0001). When these variables are included in the equation, the gender variable is not significant, but wealth variables are significant.

Results of modeling smallholders' fertilizer decisions in West, East, and southern Africa also show the main reason women do not use inorganic fertilizer is their lack of cash, capital, or credit to acquire it, not their belief in organic fertilizers or a fear of dependency on inorganic fertilizers. All of these criteria were included in decision models to use both organic and inorganic fertilizer, or either or neither of them on maize in Malawi and Cameroon (Gladwin, 1991) and in Kenya (David, 1993; Williams, 1997). Among 75 farmers used to test the model in Malawi and Cameroon, 17 (12 of them women) eliminated both organic and inorganic fertilizers because of lack of cash or credit. Only 5 farmers did not use inorganic fertilizers because of the risk of their land's becoming dependent on inorganic fertilizer.[2]

[2] Ethnographic observations also showed that African women realize the need for inorganic fertilizer. In francophone Cameroon, for example, they interplant their own food crops [e.g., maize and beans *(Phaseolus vulgaris* L.)] in the same fields with men's cash crops [e.g., coffee *(Coffea arabica* L.)]. They do this to siphon off some of the N fertilizer applied to men's crops to their own crops. After the crops are interplanted and while weeding their maize, women scrape off some of the N fertilizer still undissolved in the topsoil around the men's coffee, and push it nearer to their maize plants.

What is the morale of this story? Just as in the productivity studies cited above, gender per se has no direct effect on fertilizer use. Although women household heads apply less fertilizer than men heads, gender does not matter when one holds constant the access to cash and credit. It is gendered differences in wealth and women's lower access to cash and credit that explain their lower fertilizer use. Without as much capital or credit, women apply less fertilizer than men—and get lower yields and incomes as a result.

CONSTRAINTS TO WOMEN'S USE OF ORGANIC FERTILIZERS

Women also face many constraints limiting their use of organic fertilizers. For example, women's lack of land constrains their use of N_2-fixing beans as a sole crop (Kumwenda et al., 1996) or their interplanting of N_2-fixing tree crops with maize. Women's lack of animals and pasture land limits their access to manure; and their lack of cash constrains them from buying it. While more than one-half (44 of 75) of the women farmers surveyed in Malawi and Cameroon believed organic fertilizer was needed on maize in addition to inorganic fertilizers, almost one-half (20) of the 44 women did not use it because they lacked animals and cash to provide the manure or compost (Gladwin, 1991).

Hedgerow intercropping (HI), an agroforestry technique designed mainly to increase nutrient supply to annual crops, was tested in on-farm trials in Kenya by the International Centre for Research on Agroforestry (ICRAF), the Kenya Forestry Research Institute (KEFRI), and the Kenya Agricultural Research Institute (KARI) in the late 1980s and early 1990s. The research objectives included the selection of promising agroforestry tree species for HI, quantification of tree biomass production potential, and testing HI for its appropriateness to farmers. Leucaena *[Leucaena leucocephala* (Lam.) de Wit] and calliandra *(Calliandra calothyrsus* Meissner) tend to produce the highest biomass for use either as mulch or as fodder for livestock and thus have often been the recommended species for farmers. However, adoption of HI has been low (Swinkels & Franzel, 1997). Why? Williams (1997) used ethnographic interviews and decision-tree modeling from a sample of 40 women farmers around Maseno in western Kenya to elicit their reasons for adoption or nonadoption of HI technologies. She came to many of the same conclusions reached earlier by researchers of HI in western Kenya (David, 1992; Swinkels & Ndufa, 1993; Bekele, 1996; Shepherd et al., 1997; Swinkels & Franzel, 1997). As her decision-tree model in Fig. 9-1 shows, about one-third of the women had no knowledge of HI technology (Criterion 1). Other constraints included women's lack of access to seedlings (Criteria 2 and 3), lack of knowledge of how and where to plant them (Criterion 4), and the belief that planting trees would actually lower soil fertility (Criterion 6). More common, however, were shortage of land and labor (Criteria 8 and 10), especially in situations where agricultural intensity and population density were high.[3] Many female heads of households and women with small children felt that the large amount of labor required to coppice the trees would prevent them from

[3] It is precisely under conditions of intensive land use that extended fallow periods are not possible and the decline of soil fertility becomes an urgent agricultural problem.

using this technology. Where hedges were not frequently pruned, some farmers noted shading out of companion crops, which would result in reduced crop yields. Some farmers who had tried HI said that the trees were taking up "more room than the crops themselves" and were shading them out, or both; hence they decided to uproot the trees. In addition, many women reported problems with pests

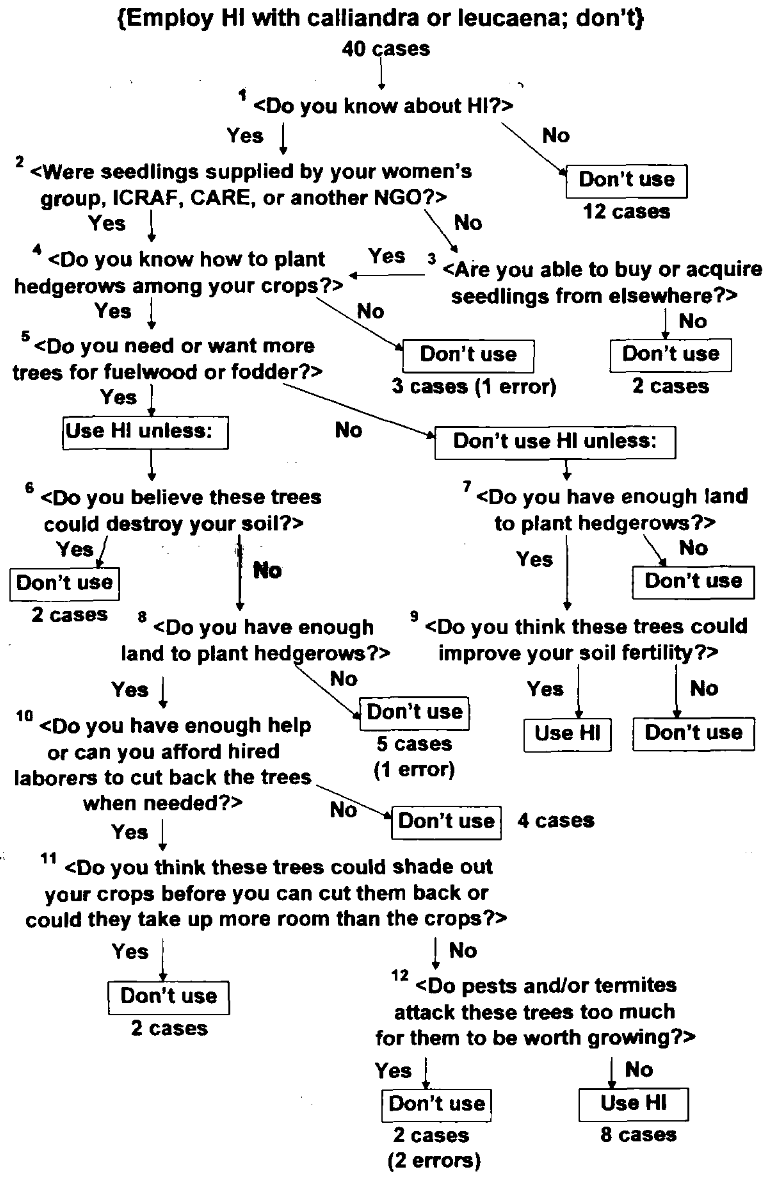

Fig. 9-1. Decision tree for the adoption or non-adoption of hedgerow intercropping (HI) by 40 women farmers from around Maseno in western Kenya (Williams, 1997).

such as termites eating the seedlings, while a few experienced attack of leucaena by the psyllid pest *(Heteropsylla cubana* Crawford) and lacked the cash to buy pesticide. This resulted in a substantial decrease in biomass production, which caused women farmers to want to uproot the trees. The cumulative result of all these constraints was that the decision model predicts only 8 of 40 women would use HI technologies in this densely populated setting. These results complement those of Shepherd et al. (1997), who found little evidence that hedgerow intercropping improved yields under farmers' conditions.

HOW CONSTRAINTS OF WOMEN CAN BE OVERCOME

How can this lack of fertilizer use by women be turned around? To include women in the process of technology transfer, project planners should collect gender-desegregated data on yields and use of inputs, plant a proportionate percentage of farmers' test plots on women's fields with women's food crops, and adopt policies specifically to target women farmers with crucial inputs of production such as fertilizer, all the while taking into consideration the severe cash constraints women farmers face. These crucial constraints of lack of cash and credit determine the quantity and type of inorganic fertilizer women apply as much as do the specific crops women plant.

Because women lack cash, we recommend as a general objective low application rates of about 25 kg nutrient ha^{-1} or 50 kg fertilizer ha^{-1} (Kumwenda et al., 1996; Larson & Frisvold, 1996; Benson, 1997). Where beans or other legumes are the women's primary crop, low rates of P (11 kg P ha^{-1} or less) may be required. In most African cropping systems where maize, other cereals, or tuber crops are women's major crops and are interplanted with various other crops, small amounts of high-analysis N fertilizer (e.g., 25 kg N ha^{-1}) can increase food production, because N is almost always the main limiting nutrient; however, low rates of soluble P fertilizer can effectively increase production of cereals on P-deficient soils. Jama et al. (1997), for example, found that 10 kg P ha^{-1} as triple superphosphate (TSP) increased maize yield and was financially attractive on P-deficient acid soils in western Kenya.

How can women farmers be specifically targeted? The development literature describes eight general options, discussed below.

Solutions Involving Use of Inorganic Fertilizer

Fertilizer Voucher Option

As a temporary measure, provide vouchers directly to cash-poor women farmers producing food crops to make it possible for them to obtain small amounts of fertilizer. A voucher system would allow an African government burdened with fiscal deficits to do something about food security by targeting the subsidy directly at women farmers who produce most of the food, and it would encourage healthy competition among private distributors in the fertilizer industry. With a voucher system, women farmers in women's clubs would receive vouchers to take to private fertilizer distributors, from whom they would buy fertilizer at a discount (similar to the way the poor in the USA buy food with food stamps or pay for housing with housing vouchers). The government would then remunerate distributors for the vouchers. The government's physical presence in the fertilizer distribution system would be minimized, and its total subsidy bill would be less than it was when fertilizer subsidies were freely extended to all growers of food and export crops, men and women alike.

The vouchers would be discontinued after a number of years, and women would buy fertilizer from local merchants on the open market at the market price, with or without credit. The temporary program of vouchers would be coupled with a plan to supervise women's application of fertilizer, to reduce leakages—defined as the use of vouchers for other than women's crops. The plan would also strengthen the revolving credit funds used by many women's clubs to bail out individual defaulting members. Clubs would receive a stipend to supervise the application of vouchered fertilizer on women's fields. Women's clubs can thus serve not only to expand credit to women but also to supervise the proper use of fertilizer vouchers.

Donors like the World Bank, however, have spent the last 10 yr removing fertilizer subsidies. Their policy now is to move toward full market cost of fertilizers (Donovan, 1996; K. Saito, 1996, personal communication). In fact, most food policy analysts recommend that input subsidies, and particularly fertilizer subsidies be eliminated entirely, because they are a common technique used to increase the profitability of intensive agriculture while keeping food prices artificially low. Timmer et al. (1983, p. 288) argue that "only when total fertilizer use is low and the ratio of incremental grain yield to fertilizer application is high" can such subsidies be cost effective, relative to higher output prices or greater food imports. African governments burdened with large fiscal deficits should therefore consider whether fertilizer subsidies represent die best use of their limited resources. After all, "someone must pay for the subsidy". Economists thus conclude that "all subsidies tend to distort the intensity of use of inputs from tiieir economically optimal levels, and significant waste is a result. Since not all inputs can be equally subsidized, output price increases will have a greater impact on productivity than will input subsidies, especially in the long run" (Timmer et al., 1983, p. 288).

This line of reasoning makes sense when applied to Asia and Latin America now; but it did not make sense during their Green Revolution era in the 1960s and 1970s, when fertilizer use contributed 50 to 75% of me increase in yields in food crops (Byerlee & Heisey, 1992), and adoption of fertilizer-responsive *modern* varieties depended on fertilizer subsidies (Harris, 1984; Van der Eng, 1994; Eicher, 1995; Goldman & Smith, 1995). Neither does it apply to current conditions in sub-Saharan Africa, where average fertilizer use—not nutrient use—is a mere 7 to 11 kg ha^{-1}, and women food producers commonly use no fertilizer (Lele et al., 1989). Larson and Frisvold (1996) conclude mat average fertilizer application rates in Africa need to increase from 10 to 50 kg ha^{-1} within 10 yr (an 18% annual growth rate) to prevent mining of soil nutrients. Near-term environmental concerns in African agriculture stem more from the persistent decline of soil fertility rather than from overuse of fertilizers, since this leaves continuous expansion of cultivation to relatively unused areas as the only option for increasing total output. Policy interventions are thus needed to encourage women food producers to increase their yields of traditional as well as modern varieties, and fertilizer subsidies in the form of vouchers are the most direct policy tool planners have at their disposal (Gladwin, 1991, 1992). From the viewpoint of the women farmers, such vouchers are preferable to an expansion of credit opportunities, because women face many constraints to credit use that men don't face: they are either too poor, too old, or lack control over a cash crop with which they can repay a fertilizer loan (Gladwin, 1992, 1996). The risk of borrowing is particularly high for them because they may have to sell some of their subsistence crop in the hunger months when their children are hungry in order to repay die loan. Rather than take that risk, they will often decide not to get credit, not to use fertilizer, and not to increase their yields.

Fertilizer subsidies can decrease diis risk for resource-poor women farmers, and so can play an important role in increasing their food production (Gladwin, 1997). For this reason, Eicher (1995) blames the donor community for failing to present a balanced view (e.g., in World Bank, 1994) of the substantial role subsidies played (and still play) in Asia's Green Revolution: "Currently donors in Africa are focused on a number of policy reforms such as correcting overvalued exchange rates and removing fertilizer subsidies rather than long-term, institution-building activities, the hallmark of donor assistance in Asia in the 1960s and 1970s. In their zeal to remove fertilizer subsidies in Africa, however, some donors are neglecting to inform African policy makers about the role of subsidies in Asian agriculture."[4]

Pinstrup-Andersen (1992) claims that fertilizer subsidies can serve as a temporary measure to compensate for the factors that make it difficult for African, as opposed to Asian, entrepreneurs to freely compete in an open fertilizer market. Among these factors are (i) the small volume of fertilizer that most African countries import, which weakens their bargaining position in negotiating for lower prices; (ii) high transportation costs within most African countries; (iii) high storage costs, which increase the expense of fertilizer distribution; (iv) unpredictable government policies and unstable institutions, which scare off private entrepreneurs from investing in input distribution systems; (v) the relative ease of government's acquiring fertilizer in the past as foreign aid; and (vi) the tendency of governments to maintain large fertilizer stocks, which may be released anytime and at any price. Pinstrup-Andersen (1992) concludes that governments should privatize fertilizer distribution in a way that assures competition, or else the private sector fertilizer distribution system may be no more efficient than the public sector system it replaces. If monopoly profits accrue, it will be more expensive. He also believes that fertilizer prices can be brought down only if, in the long run, governments invest in the infrastructure to reduce transportation and marketing costs; but until they do, "there is a place for fertilizer subsidies" to compensate for me factors resulting in very high fertilizer prices (Pinstrup-Andersen, 1992).

[4] Eicher (1995) notes that farm subsidies are still widespread in Asia; e.g., Indonesia's implicit subsidy is still 35% on fertilizer and 75% on irrigation.

Small Bag Option

Improve the availability of small amounts of fertilizer in local markets and shops by repackaging 50-kg bags of fertilizers into smaller bags. Traditionally, fertilizer has been sold in 50-kg bags. Since most fertilizer for family food production must be carried both to the home as well as to the food plots, the weight of the bag is an important issue, as well as the amount of cash or credit needed for the purchase. The transportation cost of fertilizer from the market to the home and the field also is a factor in its use. Having fertilizer available in smaller bags (complete with pictorial instructions) would make it more affordable for women and easier to carry. This strategy is compatible with the views of many economists who believe that accessibility of fertilizer is the main constraint to its increased use (Lele et al., 1989). If fertilizer were widely sold in local markets like cement, and available in weights that could be headloaded home and to the fields, women farmers would be more likely to buy it. Also, small bags reduce the risk associated with open bags of fertilizer absorbing moisture and becoming difficult to use. For these reasons, the sale of fertilizers in 5-, 10-, and 20-kg bags at local markets should encourage women farmers to use more fertilizer.

Microcredit Option

Expand the fertilizer credit market for women farmers through community banks operating on the Grameen Bank model. The Grameen Bank in Bangladesh targets very small loans to groups of virtually landless women producers (Von Pischke, 1991, p. 233; Khandker et al., 1995). With two million borrowers and a recovery rate of >90%, it is clearly a compelling model. By 1994, it served one-half of all villages in Bangladesh, lent about US$ 385 million, and mobilized another US$ 306 million as savings and deposits (Khandker et al., 1995, p. xi). The bank is unique in that its explicit goals are to alleviate poverty and create self-employment opportunities for illiterate people who own less than one-half an acre of land and have never received a loan from the formal financial system. Since 1985, it has specifically channeled credit to women, who are less empowered among the rural poor. Increasingly, women receive the bulk of the loans and are the majority of the members. Their share of total cumulative disbursement rose from a little more than one-half in 1985 to 91% in 1994; while female membership grew from 65.5% of the total in 1985 to >94% in 1994 (Khandker et al., 1995, p. 25-26). Strict observance of the norms forces group members to be accountable to each other. The second two women receive their loans only if the first two of the five women in the group repay regularly, and the group leader is customarily the last to receive credit. This creates pressure among group members to enforce the contracts and helps screen out bad borrowers. Savings mobilization is thereby encouraged. In 1994 women's savings amounted to 74% of total savings mobilized (Khandker et al., 1995, p. 31).

What lessons can Africa learn from the Grameen Bank? The first lesson is that a bank with poverty-alleviation goals can also be sustainable as a bank by lending at market interest rates. The Grameen's lending rate has been 20% since 1991 (Khandker et al., 1995, p. 66), and its subsidy dependency index (SDI) has decreased over time from 180% in the 1980s to 36% in 1994 (Yaron, 1992, 1996).

The second is that women are often better credit risks than men, since loan recovery rates for general loans have been higher for women (97% in 1992) than for men (89%) (Khandker et al., 1995, p. 18). Whether it can be replicated in Africa is now being tested by Sasakawa Global 2000 programs such as Benin's CREPs (Caisse Rurale d'Epargne et de Pret), which mobilize savings before loaning to farmers, 20% of whom are now women (Galiba, 1996).

Free Bag Option

Introduce, for a short time only, a system of grants of small bags of fertilizer targeted at the poorest women farmers who may not know the value of fertilizer or are not self-sufficient in food production. Their numbers may be substantial; Kumwenda et al. (1996) estimate they comprise 40% of the smallholder population in Malawi. After a temporary period, this program would be phased out and replaced by local merchants selling small bags of fertilizer at the market price.

Solutions Involving Organic Inputs and Biological Nitrogen Fixation

Given women's constrained supply of cash, together with the removal of price subsidies on fertilizers and their rising costs, the majority of African women farmers may be compelled to rely only on organic sources of nutrients—especially legumes that fix atmospheric N_2—as the only available strategy for increased soil fertility. At current levels of availability and use, however, organic inputs are rarely sufficient to meet crop demand for nutrients or maintain soil organic matter (Palm, 1995; Kumwenda et al., 1996). The use of inorganic fertilizer might be supplemented or enhanced with use of organic sources of nutrients (Palm et al., 1997, this publication). The following are possible options for getting organic nutrients to women farmers.

Organic Source Option

Make organic materials of farm origin more accessible. In addition to serving as sources of nutrients, organic materials can influence nutrient availability by (i) acting as an energy source for soil microbial activity, (ii) serving as precursors to soil organic matter, (iii) influencing the release pattern of plant-available nutrients, and (iv) reducing P sorption of soil (Palm et al., 1997, this publication). In on-farm trials, options would include use of green manure, animal manures, improved fallowing, biomass transfer, and legumes as sole crops in rotation or as intercropped with cereals (Giller et al., 1997, this publication). Information can be disseminated through extension workshops and field days for women and gender *training of trainers* for extension agents. Microcredit programs can be used to improve access to organic inputs for women farmers.

Biological Nitrogen Fixation Option

Make biological N_2 fixation technologies more accessible. Such N_2-fixing crops as velvetbean *[Mucunapruriens* van *utilis]*, pigeonpea *[Cajanus cajan* (L.)

Millsp.], sunnhemp *{Crotalaria juncea* L.), lablab bean *{Lablab purpureus),* and crotalaria *Crotalaria ochroleuca* G. Don and agroforestry technologies with In-fixing trees could be promoted by making seeds, small loans, and extension education more accessible, and by devoting women farmers' test plots to intercropping or rotation of legumes with cereals. Giller et al. (1994) conclude that N_2 fixation from legumes can sustain tropical agriculture at moderate levels of output.

The applicability of legume seed inoculation with rhizobia bacteria to conditions faced by African women farmers needs to be further tested. Although previous studies show legume inoculation is simple, inexpensive, and highly successful in increasing crop yield (Meisner & Gross, 1980), the African experience is that this invaluable technology is largely unavailable to women farmers who need it most (Hubbell, 1995). In Uganda, Dr. Mary Silver of Mekerere University has been using NifTal inocula strains on soybean *[Glycine max* (L.) Merr.] as a test crop. She is testing them with both women and men farmers to see if nonadoption is due to lack of knowledge about biological N_2 fixation or rhizobium inoculants, lack of access to rhizobia when needed, lack of knowledge on how to use them, lack of seed, poor soils, agronomic characteristics of the crop, inconsistency of extension advice, or to other infrastructural constraints such as the ineffectiveness of coating material such as gum arabic, syrup, and molasses, which attract hordes of ants that eat the seeds (C. Wortmann, G. Elkan, 1996, personal communication).

Organic-Inorganic Option

Make combinations of organic and inorganic inputs in small amounts more accessible. Organic materials are frequently in limited supply and hence cannot by themselves provide the productivity boost needed by smallholders. The combination of available organic materials with the judicious use of inorganic fertilizers may be a very appropriate option for women smallholders (Palm et al., 1997, this publication).

Cash Crop Option

Introduce a cash crop into women's subsistence farming systems. Sustainable food production is an important goal of development, and only when women farmers have cash will they have a sustainable way either to buy cash inputs or to repay loans for organic or inorganic fertilizers. In Malawi, women farmers are now growing burley tobacco *(Nicotiana tabacum* L.) and using its receipts to pay back loans for fertilizer use on both subsistence maize and tobacco (Brown et al., 1996; Stephen Carr, 1996, personal communication).

CONCLUSIONS

Given these diverse ways to target women farmers, which one should a rural development project use? As part of USAID's Soils Management CRSP (Collaborative Research Support Program), we at the University of Florida propose to test these different methods in several African contexts during the 5 yr from 1997 to 2002, using three evaluation criteria. First, do women fanners, once exposed to one or more of these methods to increase fertilizer inputs, continue to use them? The women themselves are the only real experts on what method works for them and whether their yields have increased as a result. Second, how much leakage from women's to men's use is there with each method? Because women lack power and money within the African household relative to men, they may be pressured to apply their fertilizer to men's export crops, not their own food crops. Third, how sustainable over time is each method relative to the other options? Given that sustainable food production and food security are our primary goals, it is necessary to see if and how the food producers themselves, most of whom in Africa are women, manage the fertility of their soils in the long run.

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Ecological Economics of Investing in Natural Resource Capital in Africa

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ABSTRACT

An ecological-economic analysis of soil fertility replenishment in Africa is proposed. Concepts from ecological economics and thermodynamics show that P and N are two different kinds of natural capital. Phosphorus is nonrenewable, whereas N is renewable. The human use of non-renewable P *inexorably* results in intergenerational externalities. The stock of P to which unborn generations will have access will be depleted as current and past uses transform a low-entropy resource into a higher entropy one. The basic economic questions are how best to liquidate nonrenewable P inventories and how best to invest in renewable N. A proposed rule stipulates that a socially optimal way of liquidating P inventories and investing in N is to invest in soil organic matter—renewable natural capital with low entropy—by an amount equal to the costs of depleting P, which includes losses in ecosystem and agricultural amenities. Such a solution is superior to sole use of manufactured fertilizers (high-entropy resource) as substitutes for P and N because it ensures the maintenance of stocks of low-entropy natural capital. The implementation of this rule necessitates applications of phosphate rock (PR) together with appropriate quantities of organic inputs, in conjunction with soil conservation measures and, in some cases, applications of mineral N fertilizer. Given the positive environmental and social externalities associated with these interventions, an equitable mechanism would be to share the costs of implementation among the different groups in society that benefit. This principle of the beneficiary pays or cost-sharing is used in European and North American agriculture.

Other authors that contributed to this publication document the extent of soil nutrient withdrawals occurring in African agriculture (Sanchez et al., 1997; Smaling et al., 1997). Even though the baseline data are not available to enable us to determine what kinds of trends in nutrient balances have taken place over time, there is a broad consensus (Stoorvogel et al., 1993; Rhodes et al., 1996) that current nutrient balances are negative in most of sub-Saharan Africa (hereafter referred to as Africa). There is also some evidence that these balances may have been negative for a number of decades in some parts of Africa (Bruno, 1930). Nutrient withdrawal is highest in the relatively fertile and steeper parts of the continent, viz., eastern and southern Africa (Smaling et al., 1997, this publication). Projections indicate that under current conditions, the extent of net withdrawals will increase in the foreseeable future throughout Africa (Stoorvogel et al., 1993). This suggests that nutrient pools will be decreasing over the coming years. Whether these decreases reach a threshold level of irreversibility and whether such a threshold even exists cannot be determined on the basis of currently available data. It is nevertheless clear that processes of nutrient depletion in African agriculture are very significant and have serious implications for future agricultural production in the continent. It also is clear that N and P are the two most limiting nutrients in African agriculture (Bekunda et al., 1997).

Economic analyses of soil nutrient use and withdrawals and soil nutrient management processes are sparse. There are nevertheless some key economic concepts, such as *natural capital,* that can help illuminate the debate about soil nutrient depletion from a different perspective than presented by other chapters in this publication.

Economists have long been interested in evaluating the *worth* of the capital of a nation (e.g., Adam Smith on *The Wealth of Nations* in the 19th century). The role played by *nature* in the formation of this capital has also been a topic much discussed since the Physiocrats—one of the first economic schools of thought initiated in France in the 18th century—argued that agriculture was the only real source of economic surplus in a nation, because it is founded on *the free gifts* of nature. Later on, Ricardo, an English economist from the 19th century, spoke of the *original and indestructible powers of the soil.* There has indeed been a long tradition in economics of considering that *nature* is boundless, and therefore, by definition in economics, a free good. Consequently, agricultural production, which is the process of transforming *nature* into agricultural goods, has traditionally been considered to be limited only by technical progress and certainly not by the resource base of agricultural systems. One of the basic assumptions of traditional or mainstream economic theory is indeed that of total substitutability of all inputs for one another, including *nature,* assumed to be totally substitutable by capital in agricultural production.

It is only since about 1970 that a few economists have started to point out that nature's productive capacity for fulfilling human needs is actually not boundless and that the purposeful manipulation of ecosystems in order to obtain agroecosystems with high rates of production or output entailed a number of environmental costs, and maybe even some irreversible losses (e.g., Georgescu-Roegen, 1971). Even more recently, since about 1990, the concept of natural capital was developed, or rather resurrected, in the context of national (country) accounts. The concept has been used to measure a country's actual net income by taking into consideration the fact that natural capital depletion (e.g., mining of mineral deposits) occurs in many countries. In most national accounts the consumption and use of natural capital, such as mining minerals, is still considered as a source of income without the corresponding decline in the stock of the resource being accounted for as natural asset depreciation. Only manufactured capital is depreciated in such accounts. Finally, the concept of natural capital has also been used since about 1994 by a few economists interested in identifying the optimal level of natural capital necessary to ensure sustainability in a country (Whitby & Adger, 1996).

These relatively recent attempts at explicitly recognizing the limits that scarce natural resources place upon agricultural production fall within the branch of economics known as ecological economics. In this chapter the issue of nutrient depletion in African agriculture is analyzed within the framework of ecological economics, which differs substantially from mainstream economics. The emerging field of ecological economics addresses the relations between ecosystems and social and economic systems. Social and economic systems are viewed as subsystems of the biosphere and thus as wholly dependent upon ecological-economic interactions. This is in direct contrast with the conventional or mainstream economic approach, which considers that all phenomena are subsumed within and obey the rules of an economic system. When discussing the role of technical progress in alleviating resource constraints, the mainstream approach is perhaps best exemplified by the following statement from economics Nobel laureate Robert Solow (1974): "The world can, in effect, get along without natural resources, so exhaustion is just an event, not a catastrophe."

The objectives in this chapter are (i) to analyze the process of nutrient depletion in Africa and the proposed soil replenishment initiative from an ecological-economics perspective, (ii) to determine what the policy implications are of this analysis, and (iii) to identify those issues that necessitate further investigation before a successful (from an ecological-economics perspective) soil replenishment project as proposed by Sanchez et al. (1996, 1997, this publication) can actually be implemented in Africa.

NATURAL CAPITAL DEFINED

Natural capital is defined here as stocks of resources generated by natural biogeochemical processes and solar energy that yield flows of useful services and amenities into the future (Daly, 1994). Thermodynamics, a branch of physics dealing with conservation and changes of energy in systems, can help to provide insights into the physical characteristics of natural capital.

In thermodynamic terms, natural capital is made up of low entropy resources (Georgescu-Roegen, 1971). The concept of entropy refers to the level of available energy or potential to be converted into *work*—as defined in physics, not economics!—of a system or a resource. A low entropy implies a high potential to be converted into work. Energy cannot be created or destroyed (first law of thermodynamics), but it changes qualitatively from a state in which it is readily available and is of high quality (low entropy) to a high entropy state where it is bound, that is, where it is of low quality and is not readily available for further transformation (second law of thermodynamics). An implication of the second law of thermodynamics is that entropic degradation (moving from a low towards a high entropy state) characterizes all production processes, including agricultural production under conditions of intensification when more and more mechanical and chemical inputs are used to replace and boost natural capital inputs that produce too low an output to satisfy human needs (Georgescu-Roegen, 1971, p. 300-304).

The above definition indicates that soil nutrients are part of natural capital. Their pools are stocks of natural capital and by virtue of their energy content they contribute to a number of flows of ecosystem and agricultural amenities and services. These flows and services include the nutrient cycles, soil fertility, and plant nutrition that in turn contribute to agroecosystem productivity, resilience, stability, and sustainability.

Natural capital can be either renewable (e.g., fish, water) or nonrenewable (e.g., minerals). The *measuring rod* of renewability is anthropocentric; it is the length of time scale needed for the natural reproduction of the stock of natural capital. Renewable natural capital can be naturally reproduced within a human time scale, through solar energy (Cleveland, 1994). Nonrenewable natural capital, in contrast, is naturally reproduced at time scales that go far beyond the interest of humans (Cleveland, 1994). The distinction between renewable and nonrenewable natural capital thus hinges on the different time scales during which natural (in contrast to human-induced) reproduction occurs.

The two nutrients considered in this chapter fall into each one of these categories. Nitrogen is renewable natural capital because its pool or stock can be increased through atmospheric biological N_2 fixation within a relatively short period of time (e.g., one season; see Giller et al., 1997, this publication). Likewise, soil organic matter (of which N is a component) is renewable natural capital because it is regenerated through photosynthesis and plant death and decomposition over relatively short spans. Phosphorus, however, is nonrenewable natural capital as it is regenerated by geochemical processes, which occur over periods of centuries to millennia. The different soil pools of P have different time scales or degrees of nonrenewability. See Buresh et al. (1997, this publication) for a discussion of these different pools.

The above definition of nonrenewable natural capital, which is based on both economic and thermodynamic concepts, implies that the continued use of such capital can only result in a decrease over time in stocks and flows of this capital and thereby in intergenerational externalities. African farmers, for example, have been reducing (mining) the stock of P in their soils over time (through crop harvests, erosion, and runoff) to the point where future generations of farmers will inherit P-deficient soils with lower productive capacity and reduced ecosystem functions. In economic terms, the action of one generation of farmers is negatively affecting the welfare of future generations of farmers. This negative externality raises issues of equity of access to nonrenewable natural capital among generations (intergenerational equity), which are discussed in the next section.

The use of renewable natural capital also can trigger intergenerational externalities, if the rate of use or harvest of a resource is greater that its rate of regeneration. Thus pools of N can be depleted or even exhausted if the rate of N uptake and withdrawals through harvest is higher than the rate at which N is fixed.

This issue is illustrated in Fig. 10—1, which shows that a shift in the production function of the agricultural sector occurs over time (from f_1 to f_3) as nutrient capital decreases and additional inputs are needed to maintain yields at the same level as before. This situation can be compared with that in southeast Asian and temperate agriculture where agricultural intensification has meant that a marginal substitution of manufactured capital (defined as manufactured and cultural capital and as the transformation of natural capital into goods and services) for natural capital has occurred over time. This substitution has been partial in the sense that, contrary to Solow's contention, manufactured capital cannot be a total substitute for natural capital, as it requires natural capital as an input into its transformation process (Daly, 1994). In addition, this partial substitution has resulted in what in thermodynamics is called entropic degradation or dissipation of energy, as low-entropy resources (e.g., soil nutrients) have been transformed into high entropy (wastes and pollution). Indeed, it is perhaps ironical but very much in the logic of the second law of thermodynamics that nitrate pollution and phosphate pollution (high entropy) are substantial forms of pollution in temperate agriculture (Whitby & Adger, 1996; Cleveland, 1994), whereas N and P are the most limiting nutrients for sub-Saharan agriculture. The energy cost of temperate agriculture has thus increased steadily as this process of partial substitution has taken place and as low-entropy natural capital has been used to an always greater extent over time. For example, the energy cost of extracting a tonne of PR to manufacture fertilizers is increasing (Cleveland, 1994). As noted by Georgescu-Roegen (1971, p. 303), the price we have to pay for agricultural intensification is the decrease in the low-entropy natural capital of the globe. Furthermore, "substitution within a finite stock of accessible low entropy whose irrevocable degradation is speeded up through use cannot possibly go on for ever (Georgescu-Roegen, 1993, p. 92)."

The foregoing discussion on definitions of renewable and nonrenewable natural capital and intergenerational externalities indicates that there are two basic ecological-economic questions, which should be posed concerning the use of natural capital. In the case of renewable N capital, the fundamental question is how best to invest in N in order to maintain the stock and flows needed for agricultural production in any given period. In the case of nonrenewable P capital, the question is different. Investment in increasing this capital (PR) is impossible over

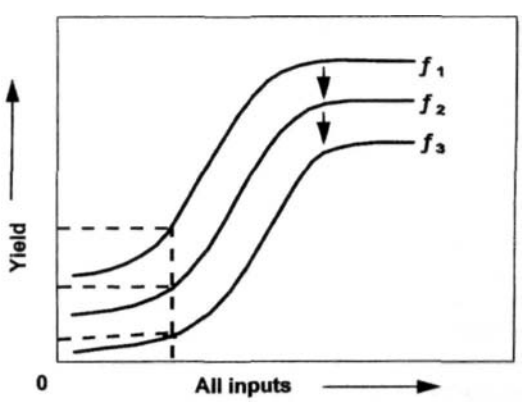

Fig. 10-1. Shift of production function with depletion of natural capital from f_1 to f_3.

time scales of human interest. The only question left then is how best to liquidate existing inventories of P (inventories of remaining stocks).

The perspective adopted in this chapter for addressing these two questions is both that of African farmers and of society at large. The stocks of N and P considered here are thus those in various fractions of farmers' soils as well as in mineral deposits.

POLICY IMPLICATIONS

Rule for Using Natural Capital in African Agriculture

In conventional mainstream economics where no limits are put onto the substitution of manufactured capital or natural capital, a rule or theorem has been derived for the *optimal* use of nonrenewable resources, such as minerals. This rule was developed by Solow (1974, p. 41), and states that "earlier generations are entitled to draw down the pool [of resources] (optimally of course!) so long as they add (optimally of course!) to the stock of reproducible [manufactured] capital." *Optimality* is defined here by reference to the rate of interest (a measure of the opportunity cost of capital) and the social rate of time preferences (rate at which society trades off the present for the future), which are concepts that need not enter into this argument. In other words, optimal depletion of nonrenewable capital requires that the marginal benefits of depletion, to those who deplete a stock of natural capital, be invested in increases in manufactured capital.

This rule has recently been modified by an ecological economist to account for the fact that manufactured capital cannot be a full substitute for natural capital (since natural capital is necessary to the formation of manufactured capital). Daly (1994) proposed that the optimal way of liquidating inventories of nonrenewable natural capital is for the net gains of liquidation to be used to finance investments in a partial substitute, namely, renewable natural capital stocks.

This rule can be applied to the case of P and N. Phosphorus is converted in situ into agricultural output and in the process is being depleted. At each step of this conversion process the benefits from increasing agricultural output should be maximized while at the same time the loss of ecological flows and ecosystem services associated with an in situ decrease in P pools should be minimized. This can be achieved when the costs of P depletion (loss of ecological amenities) are partly compensated by investments in some renewable natural capital, which will enhance soil quality.

Renewable natural capital is of course not a total substitute for nonrenewable natural capital. Rather, some renewable natural capital can be defined as a partial substitute, largely complementary to some nonrenewable natural capital, in the sense that it can improve the efficiency of energy flows and material recycling in agroecosystems. The point of this argument is that a decrease in the stock of nonrenewable natural capital (P) can, from an economic cost perspective, be partially compensated by an investment in the stock of some renewable capital. This does not imply that this renewable capital should be, in this case, an agronomic substitute for P, but simply that the *inexorable* depletion of nonrenewable P should be partially palliated by increases in soil-enhancing, renewable natural capital.

In this specific sense, soil organic matter (and N as part of soil organic matter), which was defined above as renewable natural capital, can be considered as such a partial trade-off for P for two reasons. First, it increases the efficiency of cycling of N, P, and K in agroecosystems. It thus ensures that P is used more efficiently in these systems. Second, it provides energy to drive the P cycle, which substitutes for the petrochemical energy used to manufacture fertilizer (the closest manufactured substitute). Another way of stating this is to note that the depletion of P stocks in agriculture should have two purposes: agricultural production in the shorter-term and soil fertility enhancement through increased investments in soil organic matter in the longer term.

Daly's rule for compensating, to the extent possible, declines in nonrenewable natural capital by increases in some renewable natural capital results in the case of the two soil nutrients under scrutiny in this paper into the following requirement. The *best* way of liquidating P inventories, both on-farm and in deposits, is such that the marginal costs of P depletion (for in situ P, marginal benefits for deposits) are equal (at the margin) to investments in increases in soil organic matter on farmers' fields. This assumes that from society's perspective, agricultural uses of P deposits are preferable to, or at least as beneficial as industrial uses of these deposits. A discussion of the appropriateness of this assumption lies outside the scope of this chapter. In thermodynamic terms this is a superior solution to the conventional replacement of P and N by fertilizers (e.g., triple superphosphate) because it results in increases in a low-entropy resource (soil organic matter). Fertilizers, by comparison, are high-entropy manufactured capital, which in addition further draw down P deposits.

To implement the rule proposed here in Africa it will be necessary to apply relatively large quantities of organic material together with PR coming from deposits to the depleted soils, and wherever large quantities of organic material are not feasible, applications of mineral N fertilizer (hereafter referred to as inorganic N). Excessive quantities of organic inputs, however, can be detrimental to crop yields and ecosystem functioning. While organic material has relatively low entropy, PR applications are likely to have greater entropy and inorganic N yet higher entropy (see Giller et al., 1997, this publication; Palm et al., 1997, this publication).

These applications would serve to catalyze a number of ecological functions such as decomposition, synthesis of soil organic matter, activities of soil biota, N and P cycles and in essence *jump-start* the process of agricultural production in agroecosystems. There are a number of PR deposits in Africa, which could conceivably be used as a source for these applications (Buresh et al., 1997, this publication). Applications of organic material can take many generic forms, including incorporation of compost, crop residues, litter, green manures, and biomass transfers from agroforestry and legume intercropping systems (Palm et al., 1997, this publication). The specifics of the methods of application and quantity of organic materials to be applied will vary with soil type and climate and the socioeconomic conditions of farmers. Likewise, the quantities of PR applications will be determined by soil type, climate, and socioeconomic circumstances (Sanchez et al., 1997, this publication). Finally, in addition to applications of organic matter and PR, soil erosion control measures will be needed, particularly on sloping lands, to ensure that the materials applied are not transported somewhere else.

Who Should Pay for What?

The essential point in this argument is that applications of PR alone, and (but to a lesser extent) applications of organic materials alone are insufficient to resolve the issue of nutrient depletion in Africa. It is indeed the combination of these two types of interventions, plus erosion control measures where applicable and other nutrient applications where necessary, which are called for. Such interventions will replenish the N part of the natural capital of African countries and will use up efficiently that part of this capital (P) that is nonrenewable. In addition to, and as a consequence of the catalytic role played by such applications from an ecosystem perspective, a number of positive environmental externalities will result from such applications. These range from increased C sequestration in soils and in aboveground biomass, increased biodiversity, increased watershed protection and quality of water supplies, decreased deforestation, and desertification (in some parts of Africa) to increased food security through agricultural sustainability. The benefits of increased food security would, in turn, result in a number of additional social benefits that include in particular rural poverty alleviation and employment generation through the multiplier effect. These externalities will occur, assuming that these combinations of investments in soil organic matter and applications of PR can be implemented on a sufficiently large geographical scale.

Positive environmental externalities are defined here as follows. At a given time, investments in soil organic matter and applications of PR on farmers' fields will trigger flows of nonmonetized benefits accruing to different groups in society and called environmental externalities. Local farmers will accrue some of these benefits, largely those related to increased food security at the local scale. (They will receive these benefits in addition to the increased income, which will be a direct outcome of the interventions to replenish soil fertility). National society will receive the benefits of decreased deforestation and desertification, of the protection of watershed and water supplies as well as benefits of regional and perhaps in some cases national food security. Furthermore, the national benefits of decreased rural poverty and of a more dynamic agricultural sector are potentially significant; with appropriate macroeconomic policies, agricultural growth could be one of the engines of overall economic growth in African countries (Goldman, 1994). Global society will enjoy mainly increased C sequestration and biodiversity benefits.

The fact that positive externalities will result from the large-scale implementation of the proposed rule begs the question of who should pay for this implementation. Clearly, the costs of investment rates of PR applications are currently beyond the reach of the vast majority of farmers in the African continent. Phosphate rock deposits in Togo, for example, are mined largely for export markets, and it has been hypothesized that poverty levels in the agricultural sector have hampered the development of an internal demand for soil fertility amendments in most African countries (Perkins & Roemer, 1994). In any case, the existence of externalities indicates that it would not be optimal nor effective nor equitable to expect African farmers to bear the totality of these costs. Figure 10-2 illustrates this situation. The marginal costs of these applications (MC) are compared with the marginal benefits received by individual farmers (MB,), those received by the national society (MB_n) and those received by the global society (MB_g). The exact shapes of the marginal benefit functions are an empirical issue. Some very preliminary evidence indicates that the respective marginal benefit functions represented in Fig. 10-2 may be acceptable approximations. Three case studies of the economic and environmental costs and benefits of the use of PR in Madagascar, Zimbabwe, and Burkina Faso were recently undertaken under the auspices of the World Bank. In Zimbabwe and Burkina Faso, it would appear that the global benefits of such applications are indeed greater than the national and individual ones, at the margin, and as indicated in Fig. 10-2 (Johnsen et al., 1996). The case of Madagascar is somewhat different in that PR deposits are located in islands that are classified as biodiversity *hot spots* on the World Heritage list. Exploiting these deposits would thus have significant environmental costs: a decrease in biodiversity levels.

For optimal levels of investment in soil nutrients (Q_g in Fig. 10-2) to compensate, to a certain extent, for P depletion, policy interventions will be needed. In the absence of such interventions farmers will be willing to invest only up to Q_a, assuming that they are actually able to do so, which in most cases in Africa is a heroic assumption. We know that high levels of rural poverty are indeed a constraint to any technological adoption in Africa. In 1990, for example, 30 countries in Africa had a gross national product (GNP) per capita of less than US$ 500 per year, while six countries had a GNP per capita of between US$ 500 and US$ 1000, and three countries had a GNP per capita between US$ 1010 and US$ 3330 (Tomich et al., 1995, p. 11-12). Such income levels do not leave much room for

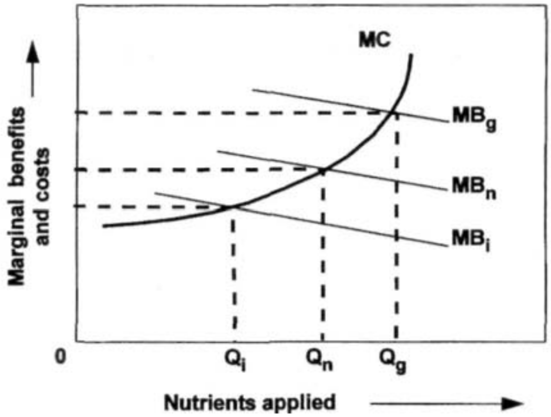

Fig. 10-2. Marginal benefit (MB) and marginal cost (MC) from P and N received by individual farmers (i), the national society (n), and the global society (g). The optimal level of investment in soil nutrients is represented by *Qi* for individual farmers, Q_n for the national society, and Q_g for the global society.

any form of on-farm investments by farmers. This is why many authors consider that rural credit schemes are a prerequisite for any improvement in African agriculture (Cole & Duesenberry, 1994). In addition to such credit schemes, however, policy interventions are needed to implement optimal levels of soil replenishment.

An equitable principle or goal for these interventions would be to spread the financial burden of investments in soil nutrients across the groups in society that benefit from this investment. This principle of the beneficiary pays would require that the global society contribute financially to these investments by an amount equal the flows of benefits it receives, which are probably greater that the flows received by other groups in society, as seen above. National societies would likewise provide funds equivalent to die flows of benefits they receive. Farmers would incur the remaining costs. Such a cost-sharing principle is not new, and there already are some mechanisms in place for its implementation.

At the global level, the Global Environmental Facility (GEF) is a mechanism for transferring funds from countries in the North to countries in the South, which undertake activities that generate global biodiversity and climate change benefits. GEF is thus the very means of implementing the cost-sharing principle proposed here between global and national societies. Another existing way to make such international transfers is C offsets. They are a type of joint implementation in which a developed country's power utility and a developing country's Forestry Department come to an agreement whereby the power utility finances reforestation efforts in the developing country in exchange for credit for the C sequestered by the reforestation. Such a mechanism could be extended to other undertakings, in addition to reforestation, and include investments in soil replenishments. The World Bank offers anodier possibility for implementing this cost-sharing principle through the granting of loans carrying no interest.

At the national level, this cost-sharing principle can be put into practice by designing a number of measures aiming at offering farmers payments in return for adopting certain management practices. The Organization for Economic Cooperation and Development (OECD) countries, for example, have recently put in place a number of mechanisms (subsidies, compensatory payments, and special grants) for ensuring that their farmers adopt practices that are environmentally sound (OECD, 1993). Compensatory payments are associated with restrictions on farming practices (e.g., to reduce nitrate and pesticide leaching into groundwaters); these compensatory payments are based on the principle of profits foregone (OECD, 1993, p. 53). Schemes for encouraging farmers to adopt environmentally sound management practices (e.g., integrated pest management; contour plowing) entail payments to farmers who adopt. The payments are directly related to the costs to the farmers of the form of management required, including the opportunity costs of this management (OECD, 1993, p. 54). A third policy instrument often used in OECD countries are special grants provided to farmers who wish to change their methods of production, from orthodox farming methods to *alternative* or organic farming. The grants cover the period of changeover during which the income of the farmers is likely to fall (OECD, 1993, p. 54). Finally, a mechanism that is used by the majority of European countries is *management agreements.* These take the form of a legal contract between public authorities and farmers, in which the latter receive regular payments in return for providing specific environmental services (OECD, 1993, p. 58). These agreements are often for a fixed number of years, but some are indefinite in length.

The USA does not really use such agreements but prefers to use cost-sharing schemes, as a variant of these agreements (Garrett & Buck, 1997). For example, in 1989 the U.S. Department of Agriculture initiated such a scheme for farmers adopting integrated crop management practices designed to reduce pesticide and fertilizer use (OECD, 1993, p. 60). Another example is that American farmers who decide to undertake tree planting to meet soil conservation objectives qualify for cost-sharing assistance from the long-standing Agricultural Conservation Program (Garrett & Buck, 1997).

It is somewhat ironical that, in addition to the mechanisms just mentioned, OECD countries also have put in place various means for controlling (in the sense of reducing) the use of fertilizer and manure production by their farmers. These means consist of a set of controls and regulations that include, for example, bans on manure spreading, maximum ceilings set on livestock densities, and ceilings on applications of fertilizers (OECD, 1993). The nitrate and phosphate pollution associated with agricultural production in Europe and North America is of course a consequence of agricultural subsidies in these countries, which are biasing P extraction and use towards farms in the North.

The point of these examples is to demonstrate that the cost-sharing principle advocated here for sub-Saharan countries has in fact been implemented by a majority of countries in the North for a number of years. Different objectives were sought by different countries, but the fact remains that farmers in these countries have been receiving various sorts of payments (and new ones are constantly being developed, as agricultural research indicates that different practices will best address various environmental problems) as incentives for adopting environmentally sound practices. It also should be remembered that such payments are taking place in countries where GNP per capita is of the order of US$ 20 000 per year. Given this international context, arguing that farmers in Africa should not receive *subsidies*, which would interfere with structural adjustment programs, as has been argued by some orthodox economists, rather appears to be a case of "do as I say, but not as I do.

The specific mechanisms that can be put in place in African countries to implement the soil replenishment strategy proposed in this chapter will vary from country to country, depending upon existing institutions and economic, agricultural, and environmental policies. For the purpose of this chapter it is sufficient to note that feasible mechanisms have been put in place both globally and in various countries that can now be used for putting into application the cost-sharing principle proposed for this implementation.

RESEARCH NEEDS

A substantial amount of research is needed before the rule proposed here for investing in the renewable natural capital nutrient of African countries can become operational. There are six principal research themes that warrant further research.

Identification of the Soils that Should Receive Nutrient Investments

The first type of data needed concerns the characteristics and the geographical location of the soils that require investments in nutrient capital. The combination of measures advocated here (applications of PR and organic materials, soil erosion control measures) needs to be targeted to specific soils. Those are presumably P depleted, including P-fixing soils with depleted soil organic matter. The problem is that not sufficient information has currently been compiled for the identification of such target soils to be possible in the majority of African countries. It is; however, essential that the geographical location of these soils be known before soil replenishment can actually be implemented. Research involving soil scientists and geographers with skills in geographic information systems and remote sensing is therefore needed to generate this type of information.

Most Effective Combination of Applications

Secondly, it is necessary to determine the most effective combinations of applications of PR, organic materials, inorganic N, and soil erosion measures for the different types of soils identified as targets for nutrient replenishment. Effectiveness is defined here in terms of efficiency of energy flows and material recycling within agroecosystems, in keeping with the ecological-economic argument developed in this chapter concerning the trade-offs between nonrenewable and renewable natural capital. The advocated combination of applications will of course vary significantly in terms of actual quantities applied, frequency of applications, type of organic inputs to be used, and overall management regimes with differences in soil types and climate (Giller et al., 1997, this publication; Palm et al., 1997, this publication). Soil scientists, soil biologists, systems agronomists, and ecologists will have to undertake this type of research.

Flows of Ecological Amenities

Once the appropriate combinations of applications are identified for the major target soils in a country, it will be necessary to quantify the flows of ecological amenities (e.g., increased C sequestration, biodiversity, decreased deforestation, desertification) that will be associated with each different combination over a period of about 7 to 10 yr. The same disciplines as above will contribute to such research. Valuations of these flows of amenities will then be needed, to determine the relative share of local versus national versus global flows. Only approximate values will be required for this purpose. A number of methods are available and have been used to assess the monetary worth of amenities such as C sequestration (see Pethig, 1994, for details). Ecological economists will be involved in these valuations.

Economic Reserves

A fourth area for further research concerns deposits of PR in Africa. An empirical issue is whether there are enough reserves of PR deposits of a sufficient quality in the continent. A related issue is how long these reserves will last. In other words, is the investment scenario proposed in this chapter and by other authors in the symposium a long-term solution, or is it rather a short-term solution because reserves that are economic and profitable to exploit are not significant? And finally, what are the costs of exploiting these reserves and of transporting PR to the different target areas and soils in a given country? Geologists, mining engineers, and economists will provide such information.

Comparison of Processed Phosphorus Fertilizer and Natural Capital Investments

On the basis of all of the above information, it will be possible to compare the investment in natural capital advocated here with applications of processed P fertilizers (such as triple superphosphate or whatever happens to be the next best alternative) in terms of their respective energetic efficiency, flows of ecological amenities, and flows of costs and benefits at various spatial scales, including food security benefits and economic growth benefits at the national scale. Economists and natural scientists will contribute to such a comparison. This comparison will be needed for determining which groups in society are the winners and the losers when natural capital investments are implemented and when processed P fertilizer is applied. This in turn is essential information for devising an effective implementation scheme in each country.

Operational Cost-Sharing Mechanism

On the basis of the results yielded by the above research themes, an operational cost-sharing mechanism will have to be developed by each country. This mechanism will be shaped by the specific policy and institutional environment of the country concerned. One of the issues it will need to address is that of the socioeconomic characteristics of the farms that should be targeted for soil replenishment efforts. As PR reserves are highly unlikely to be sufficient for applications of combinations of PR and organic material to be feasible on all target soils, and as the financial costs of undertaking these applications on all target soils (some of which will presumably be in very remote areas with poor transport facilities) are likely to be prohibitive when compared with the funds that can be raised through international and national transfer mechanisms, some priorities will have to be set. Economic theory would indicate that the farms that should be targeted are those for which returns to farmers, the national, and the global society are the highest (principle of the biggest *bang* for a given investment).

Trade-offs are likely to exist between the interests of different groups or categories of farmers. For example, applications of PR and organic materials to the farms of the poorest farmers could, under certain circumstances, bring about the highest flows of environmental amenities to the global society but relatively low benefits to the national society in terms of economic growth and food security. Similarly, applications to the farms of the better off farmers could generate high national economic benefits but relatively low global benefits. In such cases, value judgments on the part of national governments will be needed to sort out these trade-offs. Ethical considerations concerning the welfare of the poorest of the poor versus the welfare of the better off farmers also will play a role in establishing such trade-offs. Of course, the use of international transfer mechanisms in implementing the investment scheme advocated here should also help to sort out these trade-offs by providing the national government with a direct incentive to take global benefits into consideration when it identifies target farmers. Policy scientists and government authorities representing the different groups of interest involved in soil replenishment in Africa would have to be involved in the development of such an operational cost-sharing mechanism.

CONCLUSION

Based upon concepts from ecological economics and thermodynamics, it can be argued that P is nonrenewable natural capital and N is renewable natural capital. The basic economic questions are then how best to liquidate nonrenewable P inventories and how best to invest in renewable N. A theorem of mainstream economics concerning the optimal use of exhaustible resources, modified by Daly (1994) to account for the nonsubstitutability of manufactured capital for natural capital, was further modified and applied to the case of P and N. This rule stipulates that a socially optimal way of liquidating P inventories and investing in N is to invest in soil organic matter—renewable natural capital with low entropy—by an amount equal (at the margin) to the costs of depleting P.

The implementation of this rule necessitates applications of PR and organic materials, in conjunction with appropriate accompanying measures such as soil conservation and application of inorganic N fertilizer. Such interventions are beyond the financial reach of most farmers in Africa. However, it can be argued that given the positive environmental and social externalities associated with these interventions, an equitable mechanism would be to share the costs of their implementation among the different groups in society that benefit.

A quote from Holling (1994, p. 72) appropriately encapsulates the complexity of the issues discussed in this chapter. "Sustaining the biosphere [and natural capital] is not an ecological problem, or a social problem, or an economic problem. It is an integrated combination of all three."

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