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Agroecological Principles of Integrated Soil Fertility Management—A Guide With Special Reference to Sub-Saharan Africa

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Agroecological Principles of Integrated Soil Fertility Management—A Guide With Special Reference to Sub-Saharan Africa

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Foreword

Agriculture is an engine for poverty alleviation and economic growth in Sub-Saharan Africa (SSA), where about 70% of the region's population lives in rural areas and depends on agriculture for livelihood. However, loss of soil fertility and associated stagnation, or even decline, in crop productivity threaten all farming systems in SSA, causing Africa to be the only continent that has grown poorer in the past 35 years. The ability of farmers to halt soil degradation is seriously hampered by inappropriate national and regional agricultural policies, poor governance, and lack of agricultural inputs, credit, and markets to sell surplus production. These factors lead to a downward spiral of poverty and ever poorer soils. As a result, widespread and severe household food insecurity and acute poverty will likely continue to plague the region during the coming decades unless technological, economic, and sociopolitical measures are taken to accelerate agricultural growth and curtail further soil degradation. Agricultural production must increase substantially to sustain growing rural and urban populations and to maintain a strong agricultural sector. Unfortunately, most agricultural technologies developed in the past often fail to mitigate nutrient depletion or to increase crop production because of their blanket application. Often, these technologies are applied without regard to the complexity and diversity of the socioeconomic and agroecological context in which smallholder farmers operate. The challenge will be to provide farmers (and other stakeholders) with sufficiently flexible technological options. Such prototype technologies and methodologies can then be fine-tuned to suit farmers' conditions.

This guide, with special reference to SSA, was built on experiences gathered by IFDC and the Tropical Soil Biology and Fertility Institute (TSBF) in implementing research on Integrated Soil Fertility Management (ISFM) for development activities. Research was conducted jointly with support from the International Fund for Agricultural Development (IFAD) or individually with support from other donors. The guide provides soil management practitioners with basic information on ISFM and its principles and with tools that include specific frameworks for science-based ISFM application at field and farm levels. This will enable practitioners to be flexible and holistic in their approach to addressing soil-related constraints to agricultural productivity and to help develop or adapt ISFM technological options to specific ecological and socioeconomic site conditions.

I hope that this guide will increase knowledge and adoption of flexible approaches to ISFM technical option development for increased productivity and enhanced natural resources in SSA.

Amit Roy
IFDC President and
Chief Executive Officer

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List of Acronyms and Abbreviations

AE	agronomic efficiency
AEC	anion exchange capacity
CCE	calcium carbonate equivalent
CEC	cation exchange capacity
CTA	Technical Center for Agricultural and Rural Cooperation
DAP	diammonium phosphate
DST	decision-support tool
FOM	fine organic matter
ha	hectare
IFAD	International Fund for Agricultural Development
IFDC	International Fertilizer Development Center (An International Center for Soil Fertility and Agricultural Development)
ISFM	Integrated Soil Fertility Management
kg	kilogram
NGO	non-governmental organization
NUTMON	Monitoring Nutrient Flows and Economic Performance in Tropical Farming Systems
POM	particulate soil organic matter
PR	phosphate rock
QUEFTS	Quantitative Evaluation of the Fertility of Tropical Soils
RAE	relative agronomic effectiveness
RF	recovery fraction
SOM	soil organic matter
SSA	Sub-Saharan Africa
SSP	single superphosphate
TSBF-CIAT	Tropical Soil Biology and Fertility Institute-International Center for Tropical Agriculture
TSP	triple superphosphate
VCR	value:cost ratio

Agroecological Principles of Integrated Soil Fertility Management—A Guide With Special Reference to Sub-Saharan Africa

Chapter 1. Introduction

Agriculture is generally promoted as the engine of economic growth for Sub-Saharan Africa (SSA). This is not without reason; about 70% of the continent's population lives in rural areas and depends on agriculture for their livelihoods (NEPAD, 2003). Soil fertility is critical to agriculture and therefore to food security and livelihoods in SSA.

Soil fertility may be defined as the capacity of the soil to supply nutrients to a crop. In this rather narrow sense, soil fertility deals only with soil nutrient aspects, usually nitrogen (N) and phosphorus (P), and sometimes potassium (K). Nutrient capital can be defined as the stocks of N, P, and other essential elements in the soil that become available to plants in 5 to 10 years. It can be expressed as kilograms per hectare of N, P, or other nutrients within the rooting depth of plants. In its broadest sense, soil fertility can be seen as a mixture of soil chemical, physical, and biological factors that affect land potential. This definition will be used in this guide, because farmers' nutrient management practices will often result in changes in soil properties other than the chemical status. For example, compost application will have a beneficial effect on the capacity of the soil to supply nutrients to the crop and on its structure. *Integrated soil fertility management (ISFM)* refers to making the best use of inherent soil nutrient stocks, locally available soil amendments, and mineral fertilizers to increase land productivity while maintaining or enhancing soil fertility.

Soil fertility varies in the African landscape due to natural processes, such as wind erosion and dust deposition, erosion and sedimentation of soil particles with moving water, and due to human interventions including fertilization, burning vegetation, and grazing livestock. Soil fertility is also strongly related to parent rock and topography. Soils at the top of a crest to lowland toposequence are usually sandy and groundwater is well out of reach of the root zone. In such areas, sorghum and millet are common in the savanna regions and cassava and yam in the more humid zones. Going down the slope, soils become heavier in texture and fruit trees may be grown. In the hydro-morphic zone, the groundwater table is within the reach of plant roots. This zone is often used for vegetable production. In the valley bottom, clay soils are usually found, and in the wet season, such soils are often used for rice. In the dry season, vegetables and other crops can be grown, profiting from residual moisture.

Human settlements may also have a strong influence on soil fertility. Prudencio (1983) described the concentric rings of varying soil fertility status that are often said to be typical of West Africa. In this model, soil fertility and soil fertility management strategies vary with increasing distance from a village. In the first ring directly around the village, organic amendments such as household waste are used to increase soil fertility, offering good growing conditions for nutrient demanding crops like maize. In the second ring, use of organic resources declines and some application of mineral fertilizer might be observed. In the third outer ring, soil fertility is maintained through fallowing. Grazing cattle may actually mine nutrients from these areas and bring them to the first ring if cattle are kept overnight at the homestead. Farmers' labor input usually decreases going from the first ring (compound fields or infields) to the third ring (bush fields or outfields). Such ring patterns often disappear if population density exceeds a certain threshold level (Defoer et al., 2000). In such situations, unfertilized fields may be found next to fertilized fields. Instead of rings a patchwork of areas of diverse soil fertility status is observed. There may be considerable variability within the field due to termite hills, sandy patches, abandoned kraal sites, etc.

Another factor that may influence soil fertility and its management is the degree of access to resources (e.g., access to land, carts, cattle, labor, and cash). Land tenure is a very important issue. Farmers that do not own the land they cultivate may well be hesitant to invest in soil fertility, because the pay-off is not always directly visible. Access to resources often differs among household members; women may have only limited access to certain resources.

Over the last decade there has been growing concern about the fertility of soils and, consequently, the sustainability of land use in Africa. Many studies suggest that soils are rapidly degrading. Sanchez et al. (1997) stated that "soil fertility depletion in smallholder farms is the fundamental biophysical root cause for declining per capita food production in Sub-Saharan Africa." Soil degradation seems to be more prevalent in the Sudano-Sahelian regions of West Africa and in some countries in East Africa, like Sudan, Ethiopia, Somalia, and Kenya. Stoorvogel and Smaling (1990) have analyzed the nutrient balances for different cropping systems in SSA. The nutrient balances include, on one hand, major nutrient inflows from rainfall, organic manure, mineral fertilizers, symbiotic N-fixation, and sedimentation; on the other hand, are nutrient outflows through harvested produce and losses due to erosion, leaching, etc. They concluded that soil nutrient depletion is quite severe in SSA. Estimates of annual net losses were 10 kg N, 4 kg P_2O_5, and 19 kg K_2O ha^{-1} $year^{-1}$. Extrapolating these results over time (see, e.g., Sanchez et al., 1997), one can calculate 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 years from about 200 million ha of cultivated land in 37 African countries.

Breman (1990) argues that the poverty of SSA soils and the often unfavorable climatic conditions cause "overpopulation" to start at low population densities (i.e., when population densities cannot be supported by merely exploiting the natural resources available). SSA seems, therefore, to be caught somewhere between Malthus and Boserup. Malthus focused on the negative effect of diminishing returns to increased labor use in existing production systems (when more people have to be fed). Boserup emphasized the positive effects that growing population densities have on collective investments (i.e., physical and human infrastructures), which provide the incentives for technological change. According to Boserup, the positive effects would largely outweigh the negative effects. In SSA, however, population densities have reached or even bypassed the threshold levels that permit sustainable land use with the existing agricultural production systems. Technological innovation that successfully addresses rising food demand is hampered severely by a lack of infrastructure, market development, and overall economic growth (Breman and Debrah, 2003).

Fertilizers could be part of a solution to correct environmental degradation and properly address rising food demands. However, average fertilizer use in Africa is very low (about 8 kg/ha, i.e., only 1/10th of world average). The trend in consumption of NPK fertilizers in SSA over the last few decades is shown in Figure 1.

Most of the fertilizers that are used in SSA are imported. There seems to be a slight tendency for increased use of fertilizers on food crops, instead of using it for the traditional export crops (cotton). Maize production, for instance, has substantially increased in the Guinean zones of West Africa, due to the use of improved varieties, better agronomic practices, and the use of fertilizers (Byerlee and Eicher, 1997).

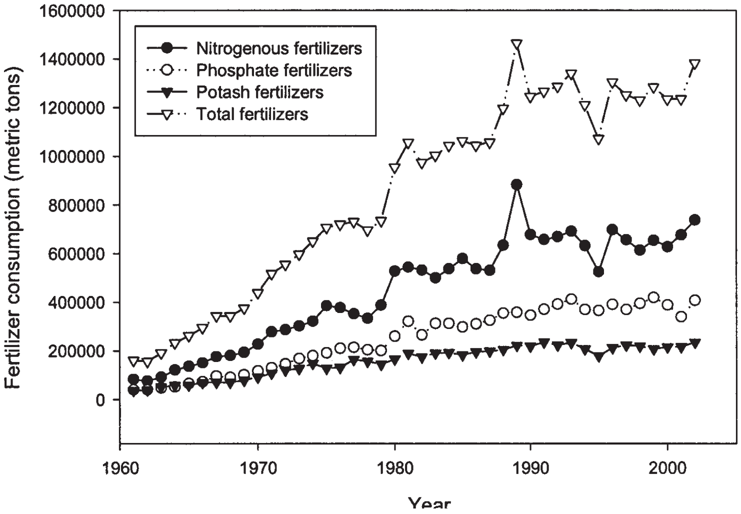

Figure 1. Fertilizer Consumption in Sub-Saharan Africa (1961-2002)

A rather desperate picture of Africa's agricultural situation emerges, according to the graph. Soil nutrient depletion is the result of increasing pressure on agricultural land, resulting in much higher nutrient outflows. These outflows are not compensated for because of the breakdown of traditional practices, such as fallowing, intercropping legume crops, mixed crop-livestock farming, and opening of new lands. In addition, poor road and market infrastructure, lack of quick access to credit and inputs at reasonable costs, lack of timely information and ineffective extension systems impede agricultural intensification based on "external inputs." However, despite the "gloom and doom" of national-level studies and analyses, there are also important nuances at the grassroots level that allow optimism (Scoones and Toulmin, 1999). The diversity of, on the one hand, socioeconomic and demographic conditions in Africa and, on the other hand, the farming systems themselves, is enormous. There are indeed several successful stories of adaptation and technological progress. There are also examples of clearly non-sustainable "coping" strategies and signs of severe land degradation.

The objective of this guide is to introduce readers to significant agroecological principles of ISFM. We hope that it will give users better insight into the complexity of soil fertility management in SSA and enhance the relevancy of agricultural research. The guide is especially intended for change agents from national research and extension agencies, non-governmental organizations (NGOs), and development projects involved in agricultural research and development. It is complementary to a decision-support tool (DST) guide for smallholder agriculture in SSA that was published by the Technical Center for Agricultural and Rural Cooperation (CTA) and IFDC (Struif-Bontkes and Wopereis, 2003).

The DST guide starts with the nature of mineral and organic fractions in the soil and their importance for a soil's nutrient supplying and environmental role (Chapter 2). The availability of organic inputs and mineral fertilizers and their capacity to provide nutrients to crop growth are discussed (Chapters 3 and 4). A discussion on the added benefits from combined use of organic inputs and mineral fertilizers is found in Chapter 5. The term "organic fertilizers" is avoided. Per definition, the term fertilizer applies to materials that contain at least 5% of one or more of the three primary nutrients (N, P, and K) in available form (Dudal, 2002).

Central to this guide is the *farming system* that is composed of several subsystems, such as rice production, animal production, maize-cassava production, and a household subsystem. The reader will be introduced to a *farm-level framework* (Chapter 6) and a *field-level ISFM framework* (Chapter 7). The farm-level ISFM framework is based on nutrient flows into and out of the farming system and between subsystems. The nutrient budgets for the different subsystems and the farm as a whole provide insight into whether nutrients are accumulated or depleted at the subsystem or farm level. Clues are provided to farmers about changing nutrient flows within the farm or at the farm level boundary to increase (or at least maintain) farm production levels in a sustainable manner. This framework is captured in the NUTMON (Monitoring Nutrient Flows and Economic Performance in Tropical Farming Systems) model (De Jager et al., 1998; Vlaming et al., 2001). More details on NUTMON can be found in the DST guide (Struif-Bontkes and Wopereis, 2003).

The field-level ISFM framework relates soil fertility and soil fertility management to crop productivity, based on concepts behind the QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils) model (Janssen et al., 1990). More details on QUEFTS can be found in the DST guide (Struif-Bontkes and Wopereis, 2003).

Chapter 8 concludes that knowledge of agroecological principles, combined with knowledge of input and output markets, may enhance the relevancy of on-farm research. This is especially true if a truly participatory learning and action-research approach is followed, where research and extension staff facilitate farmer-led research, rather than dictate the research agenda. This should enable farmers to gradually adopt more site and season-specific nutrient management, ultimately leading to enhanced and more sustainable agricultural production.

Chapter 2. Mineral and Organic Fractions in the Soil

To grow, plants need solar radiation (light), water, and nutrients. These nutrients are present in the soil, air, and water (soil solution). In general, 18 different nutrients are necessary for normal growth and full development. There are major nutrients (present in at least 0.1% of plant dry matter) and micro-elements (present in less than 0.1% of dry matter of the plant). The major nutrient coming from the air is carbon (C). Hydrogen (H) is obtained from water and oxygen (O) from water and air. These elements, C, H, and O, are transformed by photosynthesis (the engine of plant growth) into carbohydrates for the plant.

The major nutrients present in the soil are: nitrogen (N); phosphorus (P); potassium (K); calcium (Ca); magnesium (Mg); and sulfur (S). The essential micro-nutrients taken up from the soil are: iron (Fe), manganese (Mn), boron (B), zinc (Zn), copper (Cu), chlorine (Cl), cobalt (Co), molybdenum (Mo), and nickel (Ni).

Soils contain four essential constituents:

- Air (20%-30% of volume).
- Soil solution (20%-30% of volume).
- Mineral fraction (45% of volume).
- Organic matter (5% of volume).

Porosity (volume of air and of soil solution) allows roots and micro-organisms to breathe and store water. In a very dry soil, all pores (small holes and channels between soil particles) are filled with air. In a flooded soil, these pores are saturated with water. In that case, the roots of many crops cannot breathe, and they will die. Rice is exceptional because its roots can breathe in standing water. The soil mineral and organic fractions are primary sources for plant nutrients that are liberated into the soil solution.

More details follow on the nature of the mineral and organic fractions and on one crucial indicator for nutrient availability—soil acidity.

Mineral Fraction

The mineral fraction in the soil supports the plant roots and slowly releases nutrients into the soil solution. The mineral fraction is composed of elements of different sizes, i.e., clay fraction: $< 2\,\mu$ ($\mu = 0.001$ mm); loam fraction: $2 – 50\,\mu$; and sand fraction: $50\text{-}2{,}000\,\mu$ (= 2 mm). The distribution of the percentages of sand, loam, and clay determines the texture of the soil, and therefore, the percentage of coarse and fine particles. A sandy soil contains much sand, a loamy-clayey soil mainly loam and clay, etc. Soil texture is very important because it determines to a large extent the dynamics of water flow in the soil. In general, percolation rates (vertical flow) in sandy soils are much higher than in clayey soils. Together with this percolated water, nutrients flow into lower layers, sometimes out of reach of the plant roots.

The clay fraction in soils is the most important in terms of nutrient release and nutrient retention. Clay minerals have a large surface area relative to weight and some of that is negatively charged permanently, because of substitution of silicon (Si) and aluminum (Al) ions in the clay lattice by cations of lower positive charge. They can, therefore, easily exchange cations (positively charged ions, such as potassium, K^+, ammonium NH_4^+, etc.). This capacity is called cation exchange capacity (CEC) and is expressed in cmol (kg dry soil)$^{-1}$. To some extent, clay minerals can also retain anions (negatively charged ions, such as nitrate, NO_3^-) on positively charged sites. This capacity is called anion exchange capacity (AEC), also expressed in cmol kg^{-1} dry soil. The magnitude of CEC and AEC depends mainly on clay content, the type of clay mineral, and the soil pH (i.e., a measure of soil acidity, see below). The main difference between clay minerals is structure. Some clay minerals (such as illite) are of the 2:1 type, i.e., two silicate layers for every aluminum-oxide or hydroxide layer; these have large CEC capacity. Others (such as kaolinite) are of the 1:1 type (one silicate layer per aluminum-oxide/hydroxide layer) and have low CEC capacity.

Most soils in SSA contain 1:1 clay minerals with low CEC. The capacity to retain or supply nutrients to crop growth is therefore inherently low.

Organic Fraction

Organic matter plays an important role in the soil because it influences nutrient supply, structure, water-holding capacity, and soil life (Diels et al., 2003). Soil organic matter (SOM) does not consist of homogeneous material but rather of organic components that range widely in nature and turn-over time (Woomer and Swift, 1994). Soil organic matter can be physically separated into several fractions, depending on research purpose and equipment used. Two primary fractions that carry agronomic and environmental significance are: (1) particulate soil organic matter (POM), consisting of organic matter > 50 μ; and (2) amorphous organic matter, consisting of organic matter < 50 μ, associated with organo-silt and organo-clay material and referred to as fine organic matter (FOM) (Chan et al., 2002).

The POM fraction responds to management practices and is easily decomposed and rapidly lost (Mando et al., 2005a, Cambardella and Elliott, 1992). The POM fraction is, therefore, generally a good indicator of soil nutrient supplying capacity (Chan et al., 2002). The FOM fraction is much slower to mineralize due to better physical protection and is generally considered to contribute to soil stability. The FOM fraction is also seen as a good indicator of soil management-induced carbon sequestration (Chan, 2001).

Many organic materials, when applied in modest amounts (< 5 t dry matter ha^{-1}), contain sufficient N to match the N requirements of a 2 t ha^{-1} maize crop (Palm et al., 1997), but they cannot meet P requirements and must be supplemented by inorganic P in areas where P is deficient.

Especially in tropical soils, SOM content is an important factor determining the soil's CEC, because of the release of H^+ from functional groups in SOM, depending on the pH of the soil solution. At low pH, when the concentration of H^+ ions is high in the soil solution, SOM presence has no effect on CEC. CEC increases as a result of SOM only occur at pH > 5.5. According to De Ridder and Van Keulen (1990), a difference of 1 g kg^{-1} in soil organic carbon (SOC, 55% of SOM is carbon) results in a difference of 0.43 cmol kg^{-1} in CEC (at pH = 7). With higher CEC, the soil's buffering capacity (capacity to retain or release) for important base cations for plant growth such as K^+, Mg^{++}, and Ca^{++} is higher. Exchange of such base cations with acidifying cations such as Al^{+++} and H^+ will increase the pH of the soil solution. The CEC of a soil serves, therefore, also as a buffer for pH changes.

On a global scale, about 2000 Gt carbon is stored in the upper 1 m of mineral soils. This is about 4 times the C stored in terrestrial plant biomass (IPCC, 2001; Elberling et al., 2003). SOM losses are, therefore, of significant importance. Such losses may be due to deforestation, expansion of agriculture, or fuel wood gathering. Conversion to low-external input agriculture usually leads to reduced organic inputs and adverse effects of soil tillage on soil structure, exposing SOM to decomposition. Abundant information is available on the beneficial effect of conservation tillage on SOM levels from long-term experiments in temperate regions, but not much evidence exists from SSA.

Declining levels of SOM constitute a threat to the sustainability of many agricultural systems in SSA. This is caused by the high SOM decomposition rates due to the year-round high temperatures, the low capacity of soils to store FOM, and suboptimal crop management. Elberling et al. (2003) estimated that clearing and cultivation of savanna land with groundnut resulted in rapid losses of 0.06 kg C m^{-2} per year during the first 4 to 6 years in Senegal, mainly in the top 0-0.2 m. This rate declined in the following years to about 0.02 kg C m^{-2} per year. The total initial C stock in the top 1 m profile was 4.4 kg C m^{-2}. Over 40 years, losses of SOC amounted to 1.1 kg C m^{-2} or more than six times the short-term C loss associated with clearing of the above-ground biomass.

Groundnuts are harvested by pulling up the entire plant including roots; plant remains are subsequently removed and used for animal forage. Groundnut cropping in Senegal is, therefore, an extreme case in relation to C losses. Lab studies reported by Elberling et al. (2003) showed that soil respiration was 3.6 g C m^{-2} day^{-1}. During most of the year, soil respiration in northern Senegal will be zero because of water limitations. However, at the given soil respiration rate, less than 20 days of wet soil in the rainy season are enough to arrive at the C decomposition rate of 0.06 kg C m^{-2} per year mentioned above.

SOM is better protected against decomposition in clay-rich soils than in sandy soils. In general, slower turnover rates of SOM in clay and/or silt fractions are due to protective mechanisms exerted by the larger and more active surfaces of the clay minerals.

Soil Acidity

Soil acidity is measured as the activity of the H^+ ion in the soil solution (aH^+ in moles per liter), and usually expressed as the logarithm of the reciprocal of the H^+ ion activity, i.e., $pH = -\log aH^+$. The pH ranges from 1 to 14, where pH = 7 is neutral, > 7 is basic or alkaline, and < 7 is acidic. Soils are acid when a considerable portion of the exchange complex is occupied by H^+ and Al^{3+} ions instead of the basic cations, i.e., Ca^{2+}, Mg^{2+}, K^+, and Na^+. The pH is a measure of *active* soil acidity. *Potential* soil acidity is best measured by determining the saturation of the exchange complex by H^+ and Al^{3+} ions. Hydrolysis of Al^{3+} generates H^+ ions and thus acidity, according to:

$Al^{3+} + H_2O \longrightarrow Al(OH)^{2+} + H^+$
$Al(OH)^{2+} + H_2O \longrightarrow Al(OH)_2^+ + H^+$
$Al(OH)_2^+ + H_2O \longrightarrow Al(OH)_3 + H^+$

Soil acidity determines the solubility and precipitation of plant nutrients and their chemical compounds. Soil acidity is, therefore, an extremely important soil characteristic. For example, in strongly acid soils, Ca, Mg, P, B, and Mo become deficient, while Mn, Al, and Fe may become toxic to plants. In alkaline soils, the availability of Cu, Fe, Zn, and Mn is reduced (Prasad and Power, 1997).

Al toxicity may have a strong adverse effect on plant root systems. The initial and most obvious symptoms are inhibition of root growth; injured roots are characteristically stubby with reduced growth of the main axis and inhibited lateral root formation. Since root growth is restricted, the ability of the plant to explore the soil volume for nutrients and water is much reduced and water and nutrient stress may occur. Al ions also disturb active ion uptake processes across the roots-cell plasma. Al-mediated reduction of Ca, Mg, and P uptake and their translocation to the other parts of the plant have been widely reported (Haynes and Mokolobate, 2001). As a result, P, Ca, and Mg deficiency symptoms are common in plants suffering from Al toxicity (Foy, 1988). Al ions also impede P uptake through precipitation and adsorption reactions. Mn toxicity affects plant tops. Symptoms vary among plant species. Ca-deficient plants are generally stunted and young leaves do not fully unfurl. P-deficient plants also generally show stunted growth or reduced tillering in cereals. Older leaves in P-deficient plants are often purple because of the accumulation of anthocyanins, i.e., purple pigments (Hue and Ikawa, 2005).

Soil acidity in SSA may be caused by the release of CO_2 from decomposing organic matter and root respiration, root release of H^+ to maintain cation anion balance within the plant, crop removal of basic cations, application of mineral fertilizers, and nitrogen transformations in the soil, i.e., nitrification (see Chapter 4).

Chapter 3. Organic Inputs

In this chapter we first discuss the role of organic inputs building up SOM, increasing the soil's nutrient supplying capacity, and improving general growth conditions, followed by a discussion on how organic inputs can be produced in the first place. The twin objectives of building up SOM and enhancing soil nutrient supplying capacity are conflicting, because release of nutrients to sustain crops requires SOM decomposition. The traditional slash and burn farming practice in Africa is an extreme case of management of organic materials aimed at fertilization rather than building up SOM.

Role of Organic Inputs

Building Up SOM

De Ridder and Van Keulen (1990) showed that considerable quantities of organic material are needed to sustain or build up SOM. To increase the organic C content (Corg) in the top 20 cm of a soil (C-org = 3 g kg^{-1}; bulk density = 1.4 g cm^{-3}) by 1 g kg^{-1}, we assume that the relative rate of decomposition of SOM is 0.06 yr^{-1}. Using the bulk density figure, one can calculate that this soil contains 8.4 tons C ha^{-1}. A 6% loss of SOC per year is then equivalent to 0.5 tons C ha^{-1} loss yr^{-1}; to raise C-org from 3 to 4 g kg^{-1} will require an additional 2.8 tons C ha^{-1}. So, a total of 3.3 tons C ha^{-1} is needed.

If we assume that the relative rate of decomposition of straw is 0.5 kg kg^{-1} yr^{-1} and that of compost is 0.8 kg kg^{-1} yr^{-1} and the C content of straw is 0.45 kg kg^{-1} and C content of compost is 0.30 kg kg^{-1}, one can then calculate that the additional 3.3 t C ha^{-1} would require 14.7 tons ha^{-1} of straw[1] and 55.0 tons ha^{-1} of compost.[2]

Obtaining empirical knowledge about SOM development is difficult, because changes in the organic matter status of the soil happen slowly over many years. In some countries in Africa, visionary scientists have installed trials that are being conducted over long time periods. Analysis of SOM development over time in such trials allows insight into the effect of crop and soil fertility management practices on SOM build-up. For example, in a long-term trial in Saria, Burkina Faso, different organic inputs (i.e., sorghum straw, kraal manure, and compost prepared under aerobic and anaerobic conditions) were applied yearly at 10 tons ha^{-1} over a 20–year period, with and without 60 kg of urea N ha^{-1}. In addition, a fallow treatment and a treatment using only mineral fertilizers were included. SOM declined in all cropped plots compared to the fallow treatment, with the largest decline observed on plots where only mineral fertilizer was applied (Mando et al., 2005b).

Diels et al. (2003) used a simulation model (i.e., the RothC model, Coleman and Jenkinson, 1995) to simulate the fate of SOM under different production systems. Two common rotations in southern Benin are the continuous maize-cowpea and the maize-cotton relay cropping systems. Research and extension institutions have proposed alternative systems that return more organic resources to the soil, e.g., a maize-mucuna relay cropping system. The model was used to investigate the effect of the two conventional production systems (maize-cowpea and maize-cotton relay systems) and the alternative maize-mucuna relay cropping system on soil organic carbon build-up. In the conventional system, crop and weed residues, returned to the soil, amount to 8.0 t dry matter ha^{-1} yr^{-1}. The alternative system returns 12.0 tons dry matter ha^{-1} yr^{-1} to the soil. Simulations indicated that the alternative system indeed increased SOM levels, contrary to the conventional production systems that showed a slight decline. After 20 years, the increase in SOC level realized with these "high biomass production" systems was about 7 tons C ha^{-1}, equivalent to an increase of only 0.33% C in the top 15 cm of the soil over 20 years.

The simulations furthermore showed that the increase in SOM will be especially slow in the first 5 years. This case study warns against overly optimistic expectations of the beneficial effects of cropping systems that produce high quantities of biomass on SOM. Improvement of soil properties that vary proportionally to the SOM

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[1] 3.3*(1/0.45)*(1/(1-0.5)) = 14.7 tons straw ha^{-1}.

[2] 3.3*(1/0.30)*(1/(1-0.8)) = 55.0 tons compost ha^{-1}.

content (CEC, pH buffer capacity, water-holding capacity) will thus be slow. It will take a very long time for a farmer to bring about a small increase in SOM content.

Nutrient Source or Soil Amendment

Organic materials that are produced within a farming system essentially recycle nutrients, except for cases of nitrogen fixation. Organic materials that are produced outside the farming system and are imported are still bringing in nutrients at the expense of another location. Recycling of nutrients may serve as a nutrient buffer to the system, but it will not solve the problem of nutrient depletion.

Organic inputs may have a number of *direct* effects on nutrient availability (Palm et al., 1997) because they add nutrients to the soil, but their concentration is low. The organic resources database (ORD) developed by TSBF-CIAT contains valuable information on organic resource quality parameters, including macronutrient, lignin, and polyphenol contents of fresh leaves, litter, stems and/or roots from almost 300 species found in tropical agroecosystems (Palm et al., 2001).

This database can, in principle, be used to compare nutrient supply by the organic material to crop nutrient demands. However, a big question is how fast such nutrients become available and how much is ultimately recovered by the crop? Application of organic materials will generally increase the size and activity of the microbial pool. C is mostly limiting the activity of this pool, except for dry periods, where water will be limiting. The activity of the soil microbial biomass will lead to decomposition of the material, and mineralization or immobilization of plant nutrients, depending on a number of plant characteristics, including N concentration, C/N ratio, polyphenol content, and lignin content.

TSBF-CIAT has developed a decision scheme (Palm et al., 2001) that, in combination with the organic resource database, helps with organic matter management decisionmaking based on N, lignin, and polyphenol content (Figure 2).

High-quality materials (low C/N ratio, low lignin, low polyphenol) release a large proportion of N very rapidly, in advance of the main period of N-uptake by the crop and contribute little to soil organic matter build-up.

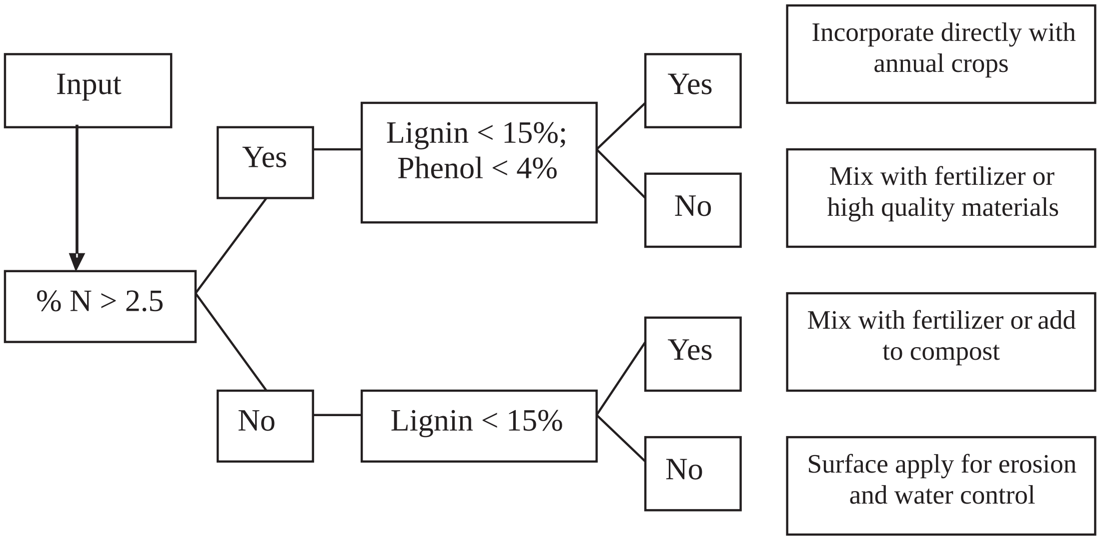

Figure 2. Decision Tree to Select Organic Materials for Use as N Source or for Other Objectives (Palm et al., 2001)

They are in principle a substitute for mineral fertilizers. However, large quantities will still be required because of the relatively low N content (rarely above 4%). Materials of lower quality (high lignin or high polyphenol) release a smaller total proportion of their N at a low continuous rate and contribute more to soil organic matter build-up. Such materials can be used as a mulch for erosion control and to conserve water, or be mixed with fertilizer or added to compost.

The incorporation of, e.g., maize straw with a relatively high C/N ratio may have a negative effect on maize yield during the first year. The transition from net immobilization to net mineralization for N occurs at about 18 to 25 g kg^{-1}. The critical value for lignin content is 150 g kg^{-1}; higher levels slow N release. The critical value for polyphenol content is 30 to 40 g kg^{-1}; higher levels lead to net immobilization of N. The C/N ratio of materials may be enhanced through composting or recycling through animals. A net P release can be expected if organic material has > 2.5 g P kg^{-1}. P may become more available upon decomposition of organic materials, because organic anions that are produced may compete with P sorption sites. Such organic anions can also complex with Al, reducing Al toxicity and positively affecting root growth (Palm et al., 1997).

Organic inputs may also have *indirect effects* on nutrient availability to the crop. They can affect root growth, the incidence of pests and diseases, and improve soil physical properties that in turn influence nutrient availability and plant growth. Mulching can help reduce weed growth, improve soil water conditions, and lead to lower soil temperatures. Application of organic inputs generally reduces Al toxicity. This increase in pH following the application of organic inputs is a short-term phenomenon (lasting a few weeks or months) but is of great importance, especially for crop establishment. As organic residues decompose, diverse organic compounds are released or synthesized and Al ions may be bound to these compounds through chelating, adsorption, or co-precipitation and so lose their toxicity. Oorts (2002) indicated that the application of organic resources to soil also improved the charge characteristic of the FOM fraction, which induced an improvement of the soil's CEC.

Vanlauwe et al. (2001) showed that for relatively fertile fields, with grain yields of about 3 tons ha^{-1} without fertilization, yield increases that can be expected from application of organic materials are virtually nil. With low soil fertility status, i.e., non-fertilized yields below 1 tons ha^{-1}, yields can be increased up to 140%, but this would lead to absolute yields hardly exceeding 1.5 tons ha^{-1}. They concluded that it is difficult to obtain substantial yield increases from isolated use of organic materials.

How to Produce Organic Inputs?

How can adequate amounts of organic inputs be produced if African soils have inherent low soil fertility, water shortage, and if food also needs to be produced on the same land? Vanlauwe et al. (2001) distinguish three production situations: (1) production at the same place and the same time as the crop; (2) production at the same place as the crop but at a different time; and (3) production at a different place.

Same Place, Same Time—Examples include agroforestry options, such as alley cropping or parkland using leguminous species. The advantages include transfer from N_2 fixed by the tree or nutrients captured from the subsoil to the crop through leaf litter decomposition. The disadvantages include potential competition between crop and trees, high investments of labor and cash, and the reduction of available land to grow crops. Alley cropping will usually take up 20% of the available space, thus crop yield needs to increase by substantially more than 20%. Such yield increases are uncertain and alley cropping and parkland have met with very low adoption rates among farmers (Dudal, 2002). If farmers can sell the wood, agroforestry options can become more interesting. Farmers in southern Benin are associating *Acacia auriculiformis* A. Cunn and maize (2 crops per year) during the first 1 or 2 years, after which Acacia is left to grow for another 2 to 3 years. Trees are generally cut in the fifth year after which maize is re-sown. Toose et al. (2005) showed that the beneficial effect of leaf litter on maize yields only lasts for 1 year. Nevertheless, with good access to maize and wood markets and over a 4-year period, the Acacia woodlot system provided considerably higher net revenue (1212€ ha^{-1}) as compared to a continuous maize-production system (814€ ha^{-1}), with a marginal rate of return of over 1000%.

Same Place, Different Time—Examples include cereal-legume rotations or relay cropping, and animal manure, derived from livestock fed from residues collected from the same field. The advantages include transfer of N fixed by the legume to the cereal and possibly improvement of soil P status due to the acidifying effect of the legume. The disadvantages include taking land out of crop production for a certain period, fast decomposition of organic matter resulting in loss of nutrients, and the need to mobilize extra labor to move organic matter (especially true for animal manure). In southern Togo, cultivation of mucuna in the short rainy season after maize cultivated in the main rainy season has been shown to give a boost to soil N supply to the succeeding maize crop (Fofana et al., 2004). However, farmers need to give up their normal maize-cassava association, which generally gives good profits. Farmers are currently experimenting using maize-mucuna on one half of their fields and maize-cassava on the other half (Tamelokpo et al., 2005) and rotate these options the next year. Another example is the use of crop residues produced on the same field. Enhancing crop yields will generally increase above- and below-ground crop residues that can serve as significant sources to build-up SOM.

Different Place—This includes cut-and-carry systems, use of household waste, and use of animal manure, not originating from the same field. The advantages include benefiting from land/nutrients that are otherwise not used and the absence of competition. The disadvantages include the need for extra labor to move organic materials, the absence of recycling of nutrients on crop land, the need for access to extra land, and the fact that manure and household waste are often of low quality.

Quantities of organic materials that can be produced or brought into a system are usually insufficient. Fernandez-Rivera et al. (1995) estimated that an average of < 0.7 ton ha^{-1} of manure is available for semi-arid West Africa. Evaluation of straw for composting in different regions in Senegal showed that a surplus existed of 1 to 2.5 tons ha^{-1} only in the south. In all other regions, all the straw is being used as animal feed, construction material, and fuel. Even if all straw being produced would be used as animal feed, manure production would still be insufficient, and substantial areas of natural pasture would be required to produce the minimum of 5 tons of manure per hectare of arable land (De Ridder and Van Keulen, 1990). Where fertility depletion is already high, relatively small amounts of crop residues and animal manures are produced, and mineral fertilizers may become the principal sources for building up nutrients in soils.

Chapter 4. Mineral Fertilizers and Soil Amendments

A commercial fertilizer is a material that contains at least one of the plant nutrients in chemical form that, when applied to the soil, is soluble in the soil solution phase and "available" by plant roots (Roy, 2003). Usually three numbers are used when describing the content (grade) of mineral fertilizers. These three numbers refer in order to the content of N, P, and K. Often P and K content is expressed in the oxide form, i.e., P_2O_5 and K_2O. The term "mineral" or "inorganic fertilizers" is preferred over "chemical fertilizers" because this avoids lumping mineral fertilizers and pesticides together as "agrochemical inputs." All fertilizers provide nutrients to the crop and are "chemical," whether they are of mineral or organic origin, natural or manufactured (Dudal, 2002).

Types of Mineral Fertilizers

Mineral N Fertilizers

Nitrogen is an essential component of amino acids, chlorophyll, enzymes, and nucleic acids in the plant and is one of three primary nutrients. Leaf N concentration is closely related to the rate of leaf photosynthesis and crop biomass production. N is often the limiting element for crop growth; however, other macronutrients such as P or K may become limiting if sufficient N is applied to the crop. Nitrate (NO_3^-) and ammonium (NH_4^+) are the major N-sources available for plant uptake.

Nitrogen is abundantly available in the atmosphere, but only a very limited number of plants and trees can fix nitrogen directly from the air in forms usable by plants. This biological N fixation is driven by micro-organisms. In industrial N fixation, nitrogen and hydrogen are combined under high temperature and pressure to form ammonia. The hydrogen in this reaction is derived from natural gas, petroleum, or coal. Urea is formed from the reaction of ammonia and carbon dioxide under heat and pressure. Similarly, when ammonia is combined with nitric acid under heat and pressure, ammonium nitrate fertilizer is formed.

There are three forms of mineral N in fertilizers. Nitrates supply NO_3^- ions, ammonium salts supply NH_4^+ ions, and amides contain N in $-NH_2$ (amide) form, such as in urea. The amide-bound N in urea is converted to ammonia and ammonium in the soil through hydrolysis by the urease enzyme. Acid soils slow the rate of urea hydrolysis. The conversion of urea to ammonia may induce gaseous losses through volatilization. Such losses are especially likely in alkaline soils (high pH).

Ammonium is usually either adsorbed by clay particles or quickly converted to nitrate through the process of nitrification, except in acid and flooded soils (i.e., reduced soil conditions). Nitrate anions are directly available for the plant, but are also easily leached out of the root zone. Through nitrification, ammonium is first oxidized to nitrite and then to nitrate by two different groups of micro-organisms. Nitrification releases hydrogen ions (H^+), which may lead to acidification. If all nitrate ions produced through nitrification were absorbed by plant roots, excretion of OH^- by the plant would neutralize the hydrogen ions. Nevertheless, in general, only a fraction of total nitrate produced is absorbed by the plant roots.

Besides differences in the chemical form of N, differences also exist in relation to the accompanying nutrients. The best example is diammonium phosphate (DAP), which contains 46% P_2O_5 and 18% N.

Mineral P Fertilizers

P is an essential component of adenosine triphosphate (ATP), nucleotides, nucleic acids, and phospholipids. Its primary functions are in energy storage and transfer and the maintenance of membrane integrity. P in cereals promotes tillering and root development. P fertilizer application is necessary if the plant's root system is not fully developed and the native soil P supplying capacity is insufficient. Uptake occurs when phosphorus is present in the soil solution in the form of $H_2PO_4^-$, HPO_4^{2-}, or PO_4^{3-}.

Essentially all fertilizer phosphorus is derived from mined ores (Roy, 2003). Phosphate rock (PR) is of sedimentary or igneous (bird excrements) origin. PR of sedimentary origin is generally more reactive than igneous PR. PR is usually converted into a more readily plant-available form in finished fertilizers using sulfuric acid. PR generally contains about 32% P_2O_5, compared to 46% P_2O_5 for triple superphosphate (TSP) and 20% P_2O_5 for single superphosphate (SSP).

About 2.0 million tons of PR is used worldwide for direct application. This amount represented only about 1.7% of the total P consumption in 1998 (Roy, 2003). Direct use of PR meets serious drawbacks. PR has relatively low P content in comparison with most manufactured fertilizers; this increases shipping cost. The very fine grinds that are required to encourage solubility are difficult to handle and to apply. The main drawback, however, is agronomic (Roy, 2003). The relative agronomic effectiveness (RAE) of PR with respect to water-soluble P fertilizers, such as TSP, depends on the origin and the chemical and mineralogical nature of the particular rock, the pH and other characteristics of the soil, management practices, and the crop species.

Chien and Menon (1995) compared the RAE of various PR sources; RAE ranged from 19% to >100% (with RAE of TSP = 100%). IFDC has developed a decision-support tool (phosphate rock decision support system, PRDSS) to estimate the initial response to phosphate rock application in comparison to water-soluble phosphate fertilizers, such as TSP (Singh et al., 2003).

To be most effective for crops, PR should be broadcast and incorporated into the soil to maximize the surface contact of PR particles with the soil. Liming of acid soils is a common practice to raise soil pH and decrease Al toxicity for optimal crop growth. However, the higher pH and the increased exchangeable Ca resulting from liming are detrimental to PR dissolution. In general, the RAEs of PRs with respect to water-soluble P sources are higher for long-term or perennial crops than for annual crops (Chien and Menon, 1995).

Mineral K Fertilizers

The functions of K in the plant are numerous. K activates or catalyzes a host of enzyme actions, transports nutrients and assimilates them within the plant, maintains the structural integrity of the plant cell, regulates turgor pressure, mediates the fixation of N in leguminous plant species, and protects plants to some degree from certain diseases and lodging. Potassium is relatively abundant in the earth’s crust. The K fertilizer industry is based on very large deposits of water-soluble potassium minerals resulting from the evaporation of shallow seas or natural lakes over a geological time span. The most widely used K salts in agriculture to produce K fertilizers are double salts that contain important quantities of Mg and sulfur (S) in addition to K (Roy, 2003).

Bulk Blends

N, P, and K materials are all available from basic producers in granules. Granular mixed fertilizers of almost any grade can be made by simple proportioning and dry blending of granular N, P, and K materials. In 1999/2000 about 57 million mt of bulk-blended fertilizers was produced. This corresponded to about 16% of the global fertilizer production. Most NPK blends are prepared with DAP (diammonium phosphate of 18-46-0 grade). Granular TSP is used for no-nitrogen (PK) grades, but for NPK blends, TSP has the disadvantage of being incompatible (reactive) with urea (Roy, 2003).

Blends are prepared following specific nutrient requirements for crops. Cassava and plantain, for instance, require much more K relative to N than maize (Table 1).

Soil Amendments

Gypsum ($CaSO_4 \bullet 2H_2O$) is a mineral that occurs as a natural deposit in semi-arid and arid regions with low solubility in water. Gypsum is especially used to recuperate sodic soils that have by definition a very high percentage of sodium on the exchange complex (>15%). Such sodic soils often have a degraded soil structure because of the collapse of clay minerals. Gypsum is usually incorporated at land preparation over a depth of 0-

Table 1. N:P:K Ratios of the Harvested Products of the Important Crops in SSA (Wichmann, 1998). Values Between Brackets Are Standard Deviations.

Harvested Products	N:P:K Ratio
Maize	100:21(3):29(5)
Cassava	100:17(7):174(81)
Yam	100:12(3):107(26)
Plantain	100:9(1):224(17)
Soybean	100:8(1):27(6)

15 cm. Gypsum reacts with sodium salts (e.g., sodium carbonate) and replaces exchangeable Na on the exchange complex, which is then leached out as sodium sulfate (Prasad and Power, 1997).

Liming materials are used to recuperate acid soils. Liming improves soil pH, and therefore provides a better environment for plant growth. Because of increased pH, Al or Mn toxicity is prevented and P and Mo availability is increased. Micro-biological processes such as nitrification and N-fixation also improve. Liming may also contribute to improved physical soil properties because of increased microbial activity (Prasad and Power, 1997).

The most commonly used liming material is limestone or calcium carbonate ($CaCO_3$) and all other liming materials are evaluated relative to their effectiveness compared with calcium carbonate (expressed in calcium carbonate equivalent, CCE, where $CaCO_3$ has a CCE of 100). Limestone deposits are found all over the world. It is usually mined by open-pit methods and using explosives. Broken rock pieces are crushed to sizes of < 2.5 cm and further ground or pulverized. The quality of commercial limestone is generally 90%–98% CCE. Other liming materials include calcium oxide (CaO) with a CCE of about 180%; calcium hydroxide ($Ca(OH)_2$) with a CCE of about 135% and dolomite ($CaMg(CO_3)_2$) with a CCE of about 110%.

The liming requirement of a soil depends on soil acidity level and the level of exchangeable Al^{3+} that a crop can tolerate; indicative threshold values of Al tolerance for selected crops are given in Table 2. Liming requirements are calculated using empirical formulas that are a function of Al saturation on the soil's exchange complex.

Choosing the Right Type of Mineral Fertilizer

The choice of fertilizer will depend on the targeted crop, the local availability/cost, and the soil/climate. For example, for soils with a low buffering capacity, it would be unwise to use ammonium sulfate as a source of N

Table 2. Indicative Threshold Values of Al Tolerance for Selected Crops, Expressed as a Function of Saturation of the Cation Exchange Complex With Al

Crop	Threshold Values for Al (% saturation of exchange complex, CEC)
Maize	30
Sorghum	15
Soybean	0
Cotton	0
Yam	30
Rice	40
Groundnuts	40
Cowpea	60
Cassava	75

Source: NuMaSS Database (Vlaming et al., 2001).

due to its soil acidifying potential. In humid environments, however, it is better to avoid nitrate-based fertilizers because these may be quickly leached. Increasing cropping intensity will generally lead to a greater need for K, especially for bananas and root and tuber crops. Acid soils may need liming, but some crops such as cassava and yam do quite well on acid soils. Leguminous crops are usually limited by phosphorus, since they can obtain nitrogen from the air. DAP is, therefore, a good fertilizer for grain legumes because it contains more P than N while the latter could serve as starter-N. The irrigated rice systems in the Office du Niger in Mali now respond to potassium after more than 30 years of mono-cropping and straw removal (Wopereis et al., 1999).

A major constraint to farmers is, however, that the right type of fertilizer for the target crop is often not available. For example, the cotton fertilizer used for maize in Benin contains too much P compared to N for application to maize (Vanlauwe et al., 2001). Wopereis et al. (1999) voiced similar concerns about the use of cotton fertilizer in irrigated rice-based systems in Burkina Faso.

Efficiency of Mineral Fertilizers

The agronomic benefits of mineral fertilizer applications can be defined in a number of ways. The agronomic efficiency (AE) of a particular nutrient, e.g., N is defined as:

$$AEN = (Y_F - Y_0)/N_{appl}$$

Where:

AEN is the agronomic efficiency of fertilizer N, expressed in (kg harvestable product/kg N applied)
Y_F refers to yield (kg/ha) obtained with fertilizer N
Y_0 refers to yield (kg/ha) obtained without fertilizer
N_{appl} is the level of fertilizer applied (kg N/ha)

The AE of other nutrients can be obtained in a similar way.

The recovery fraction (RF) of applied nutrients, e.g., N is defined as:

$$RFN = (N_{uptF} - N_{upt0})/N_{appl}$$

Where:

RFN is the recovery fraction of applied N (kg N uptake/kg N applied)
N_{uptF} is plant N uptake at harvest with fertilizer N (kg N uptake/ha)
N_{upt0} is plant N uptake at harvest without fertilizer (kg N uptake/ha)
N_{appl} is the level of fertilizer applied (kg N/ha)

The RF of other nutrients can be obtained in a similar way.

The internal use efficiency of nutrients, e.g., for N is defined as:

$$IEN = (Y_F - Y_0)/(N_{uptF} - N_{upt0})$$

Where:

IEN is the internal efficiency of N (kg harvestable product/kg N uptake)
Y_F refers to yield (kg/ha) obtained with fertilizer N
Y_0 refers to yield (kg/ha) obtained without fertilizer
N_{uptF} is plant N uptake at harvest with fertilizer N (kg N uptake/ha)
N_{upt0} is plant N uptake at harvest without fertilizer (kg N uptake/ha)

The IE of other nutrients can be obtained in a similar way. Note that AEN = RFN * IEN.

It is important to realize that the agronomic efficiency (AE) of a nutrient like N is influenced by many factors, other than fertilizer application. To increase the efficiency of mineral fertilizers, it is essential to adopt an integrated crop management approach to manage all growth limiting or growth reducing factors (see also Chapters 6 and 7). With good crop management, the efficiency of mineral fertilizers can be further influenced by considering rates, timing, mode of application, and placement of the fertilizer.

Socioeconomic Considerations

A major problem for farmers in Africa is the price tag attached to mineral fertilizers. Vanlauwe et al. (2001) showed that a 50-kg urea bag would cost US $7.50 in Germany in 1999 versus US $13-$17 per 50-kg bag of urea in Nigeria, whereas Nigeria produces a significant amount of urea itself.

Usually the value:cost ratio (VCR) is used to evaluate the economic benefits of fertilizer use, calculated by the value of the additional yield after fertilizer application and divided by the cost of fertilizers to achieve this. VCRs below 2 are considered too low for farmers to evaluate and adopt. Marginal analysis calculates marginal rates of return between options, proceeding in steps from a lower cost option to that of next higher cost, and compares those rates of return to the minimum rate of return acceptable to farmers. It is assumed that farmers should be willing to adapt an option if the marginal rate of return of that treatment is greater than the minimum rate of return. The minimum rate of return is for the majority of situations between 50% and 100% and tends to be toward 100% for technologies that require new skills (Crawford and Kamuanga, 1991).

An example of how this works is given in Table 3 for a maize crop grown after cutting Acacia auriculiformis woodlots in southern Benin. Maize fertilizer response was determined over 2 consecutive years after cutting the

Table 3. Effect of Previous Acacia Auriculiformis Woodlots and Mineral Fertilizer Application on Maize in the Primary Growing Seasons of 2001 and 2002; Hayakpa, Southern Benin

Yield gains are calculated as a function of a non-fertilizer control.
Costs only include purchase costs of fertilizer in this simplified calculation.
Benefits are calculated from yield gain * grain price, without adjustment for additional harvesting and post-harvesting costs incurred.

Acacia	N, P, K Fertilizer	Yield Gain Over Control	Fertilizer Costs	Value to Cost Ratio	Marginal Rate of Return
	(kg/ha)	(t/ha)	(euro/ha)	(-)	(%)
First Year—2001					
With	60N: 0P: 0K	0.19	45	0.6	65
	60N: 10P: 0K	0.74	62	1.8	487
	60N: 10P: 60K	0.55	125	0.7	-46
Without	60N: 0P: 0K	0.23	45	0.8	78
	60N: 10P: 0K	1.00	62	2.5	681
	60N: 10P: 60K	1.30	125	1.6	73
Second Year—2002					
With	60N: 0P: 0K	0.29	45	1.0	99
	60N: 10P: 0K	1.14	62	2.8	752
	60N: 10P: 60K	1.26	125	1.5	29
Without	60N: 0P: 0K	0.30	45	1.0	102
	60N: 10P: 0K	0.76	62	1.9	407
	60N: 10P: 60K	1.15	125	1.4	95

woodlots, and on control plots without Acacia. The VCR for mineral fertilizer application is generally below 2, except for the treatment where 60 kg N and 10 kg P is applied per hectare. This treatment also shows the best marginal rate of return.

Environmental Considerations

Mineral fertilizer use in industrialized countries is often accompanied by environmental concerns due to excessive applications. Overuse of mineral fertilizers is not a concern in Africa. On the contrary, the big environmental issue is related to depletion of soil fertility, exactly the opposite of what is often occurring in the industrialized countries.

Such depleted soils produce insufficient organic material to fuel agricultural growth needed in SSA, and mineral fertilizers are, therefore, indispensable. However, application of mineral fertilizers may, in the long run, lead to decreasing base saturation (a decline in the percentage of base cations, i.e., Ca, Mg, K, and Na on the soil's exchange complex) and acidification of the soil. N fertilizers may cause increasing K deficiency, decreasing pH and Al toxicity. Ammonium sulfate as N-source will acidify the soil, but urea and calcium ammonium nitrate much less so. A small difference in pH near pH = 5 can have dramatic effects. Aluminum ions will be liberated from the clay lattice and enter soil solution, with toxic effects on the crop.

On the other hand, long-term inputs of mineral fertilizer may delay the decrease in SOM content upon cultivation by providing more crop residues including roots. Vanlauwe et al. (2001) showed that the organic C content of plots with fertilizer application is usually comparable to or slightly higher than the C content of plots without the addition of external inputs. Changes in soil N content varied considerably, with half of the soils showing a decrease in soil N content. Vanlauwe et al. (2001) attributed this to inefficient use of applied fertilizer N and mining of the soil N pool.

The acidifying capacity of N fertilizers may even be beneficial by increasing soil P status or availability of P from PR (Vanlauwe et al., 2001). If pH levels drop too much, acidification can be counteracted through liming or by using other types of nitrogen fertilizer. Application of P fertilizer usually improves general soil fertility by the addition of Ca and S, depending on the type of P fertilizer.Phosphate rock has considerable liming potential.

Chapter 5. Combined Use of Organic Inputs and Mineral Fertilizers

Increased use of mineral fertilizer in West Africa is hampered by high costs and low efficiency in general. Still, sustainable intensification will require large inputs of mineral fertilizer in Africa. The question is then how organic inputs can contribute to improvement of the efficiency of mineral fertilizers. Nitrogen is of significant concern, because it is the most mobile macronutrient, and often most limiting to crop growth. Vanlauwe et al. (2001) formulated a "direct" and an "indirect" hypothesis for N.

The direct hypothesis was formulated as: "Temporary immobilization of applied fertilizer-N after application of organic matter-C may improve the synchrony between the supply of and demand for N and reduce losses to the environment."

The indirect hypothesis was formulated as: "Any organic matter-related improvement in soil conditions affecting plant growth (except the nutrient X) may lead to better plant growth and consequently enhanced efficiency of the applied nutrient X."

Whether direct or indirect, added benefits from combined use of organic inputs and mineral fertilizers in terms of crop yields can be calculated as:

$$AB = Y_{comb} - (Y_{min} - Y_0) - (Y_{org} - Y_0) - Y_0$$

Where:
AB signifies added benefits of combined use of organic inputs and mineral fertilizers (kg/ha)
Y_0 refers to yield in the control treatment (kg/ha)
Y_{fert} refers to yield in the treatment with sole application of mineral fertilizer (kg/ha) Y_{org} refers to yield in the treatment with sole application of organic inputs (kg/ha) and Y_{comb} signifies yield in the treatment receiving both mineral fertilizer and organic inputs (kg/ha).

There is substantial evidence of both direct and indirect interactions occurring from simultaneous use of mineral fertilizers and organic inputs (e.g., Iwuafor et al., 2002; Vanlauwe et al., 2002; Fofana et al., 2004). Farmers will usually have access to organic materials that are of relatively low quality, i.e., with high C/N ratios. Such material is likely to cause a direct interaction with mineral N fertilizer application. It is, however, uncertain whether this will lead to a better synchrony between N demand and supply because immobilized N needs to be mineralized when crop demand is high. Although application of organic resources may improve fertilizer N use efficiency, good general crop management, improved fertilizer application practices, such as deep placement of fertilizer N, increasing the number of splits and better timing of fertilizer N applications are more likely to enhance fertilizer use efficiency.

On the other hand, there is considerable evidence (e.g., Wopereis et al., 2005) that mineral fertilizer efficiency can be enhanced if applied on relatively fertile soils as long as resulting yields are still far off potential yields in the environment (for a detailed discussion on this aspect see Chapter 7). This last principle is illustrated in Figure 3, showing AB from application of N fertilizer for maize yield on infields ("compound fields") and outfields in northern Togo. Two years are shown, one with well-distributed rainfall (1999) and one with poorly distributed and low rainfall (2001). N fertilizer application on infields resulted in added benefits of between 0.3 (1999) and 0.6 t ha^{-1} (2001) as compared to outfields at 100 kg N ha^{-1}. At lower N dose, no added benefits were observed in 1999 and an added benefit of 0.3 t ha^{-1} was observed in 2001. Wopereis et al. (2005) explained these results by better water retention on infields as compared to outfields, i.e., an indirect effect on N availability for the maize crop.

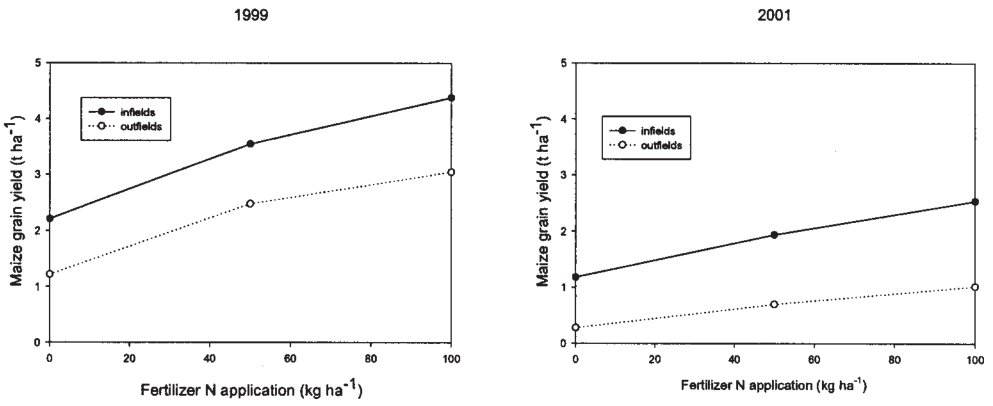

Figure 3. Calculation of the Added Benefits Generated by Applying N Fertilizer on Infields as Compared to Outfields in a Year With Good Rainfall (1999) and in a Year With Low and Poorly Distributed Rainfall (2001) During the Maize Growing Season

Long-term soil fertility experiments are rare in SSA, but they will often be our best source of information to see how soil fertility evolves under a given set of crop management practices. Data over prolonged periods (e.g., Pieri, 1995) indicate that yields will decline if no external inputs are used and this goes hand in hand with a decline in SOM. Treatments using only inorganic fertilizer often also show a decline in yield after some time, because of side effects, such as acidification, next to a decline in soil organic matter status. Prolonged treatments using only organic amendments also show yield decline, but the positive impacts are usually sustained longer than for inorganic fertilizer alone in many cases. However, the amount of organic inputs required to sustain yields is usually considerable, because nutrient contents are very low. Best results are usually obtained when treatments combine inorganic and organic inputs. The inorganic source provides the necessary nutrients and the organic source the build-up of soil organic matter, cation exchange capacity, water retention capacity, and soil structure (Scoones and Toulmin, 1999). Nevertheless, in order to achieve efficient fertilizer use, mineral fertilizer application strategies should account for nutrients brought in with organic inputs that are readily available for plant uptake (i.e., in the case of high quality materials). Higher fertilizer rates may be needed if low quality materials are used because of temporary immobilization of nutrients. In the long run, fertilizer rates should be gradually adjusted to account for nutrient stocks built up by long-time application of organic resources. This is illustrated by the considerable differences in maize yields obtained without fertilizer on infields and outfields in Figure 3. These aspects are discussed in more detail in Chapter 7.

Chapter 6. Farm-Level ISFM Framework and Applications

Analyzing soil fertility management takes into account stocks and flows of nutrients at farm and field levels and sometimes beyond (e.g., in case of considerable between-farm flows on a toposequence). This type of analysis is sometimes referred to as “nutrient budgeting.” Nevertheless, soil fertility is more than nutrients alone. Certain interventions may improve the physical and biological properties of the soil, yielding important benefits, such as better water retention and improved recovery of mineral fertilizer by the plant. Nevertheless, it is often convenient and advisable to focus on nutrient management, with special emphasis on the macronutrients, i.e., nitrogen (N), phosphorus (P), and potassium (K) because they are significant driving factors for crop growth.[3] A farm may consist of several fields, various animal and/or crop-based production systems, and the household system. The fertility of the soil (nutrient stocks and service flows) is transformed by the various production systems in harvestable produce contributing to the well-being of the farmer family.

A wealth of literature is now available demonstrating the nutrient budgeting approach, first pioneered by Stoorvogel and Smaling (1990). For a given soil nutrient (usually N, P, or K) the equation reads:

$$\text{Balance} = [IN1 + IN2 + IN3 + IN4 + IN5 + IN6] - [OUT1 + OUT2 + OUT3 + OUT4 + OUT5 + OUT6]$$

where:

IN1 = mineral fertilizers; IN2 = organic fertilizers, such as animal manure; IN3 = atmospheric deposition; IN4 = biological fixation (for N only); IN5 = sedimentation; IN6 = uptake by deep-rooted plants; and OUT1 = harvested production; OUT2 = crop residues; OUT3 = leaching; OUT4 = gaseous losses; OUT5 = soil erosion; OUT6 = other losses, such as outflow to deep pit latrines.

This equation can be applied at different scales, from field to region and even country level. Some of these parameters are easier to measure or estimate than others. Nutrient inflows from atmospheric deposition, biological N-fixation or losses through leaching or as gases are invisible and not easy to comprehend by farmers. They can be calculated using “transfer functions” and computer models (e.g., NUTMON; Vlaming et al., 2001). Estimations are often combined with actual measurements, which may lead to considerable errors. Scaling-up of plot-based budgeting exercises may also lead to erroneous results. Such exercises will usually overestimate nutrient gains or losses from a system because these will be considerably less on a catchment scale. For example, mineralized nitrogen after the first rains will be leached down and lost from the soil at the top-end of an inland valley system, but will be a gain to the lowlands at the bottom end of the slope. It is clear, however, that insight in nutrient flows, even if these are restricted to “visible flows” may be extremely useful.

Farmers may manipulate soil fertility in several ways. They may (1) add nutrients to replenish stocks and flows in the soil; (2) block nutrient flows leaving the farm (“leaks in the system”); (3) do a better job in recycling nutrients that are not optimally used within the farm; or (4) increase the efficiency with which nutrients are used by the various production systems. These different interventions may help to intensify agricultural production and increase outputs. While measure (1) focuses on additional nutrient flows into the system, measures (2), (3), and (4) ensure greater efficiency of inputs used. A farm-level analysis (this chapter) is useful for all four measures, whereas a field-level analysis (Chapter 7) is especially crucial for measure (4).

6.1 Farm-Level Framework

Dixon et al. (2001) have summarized the 14 major farming systems in Africa and classified these in terms of growth potential and potential for poverty reduction. They selected the five most important systems:

- Irrigated systems (rice, vegetables, livestock): low potential for poverty reduction, high potential for agricultural growth.

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[3] Other driving factors include e.g., solar radiation, temperature, and water availability.

- Tree crop system (tubers and cash tree crops): high potential for poverty reduction and moderate/high potential for agricultural growth.
- Cereal-root crop mixed system (maize, sorghum, cassava, yams, livestock, off-farm activities): low potential for poverty reduction, high potential for agricultural growth.
- Maize-mixed systems (maize, cassava, cattle remittances): high potential for poverty reduction, moderate/high potential for agricultural growth.
- Agro-pastoral millet/sorghum systems (millet, sorghum, livestock, remittances): high potential for poverty reduction, low/moderate potential for agricultural growth.

Each of these major production systems in Africa consist at the farm level of a number of fields, various animal and/or crop-based production systems and the household system.

Three subsystems can be distinguished within the farm system: the crop production system (*cps*), the animal production system (*aps*), and the household system (*hhs*) (Figure 4).

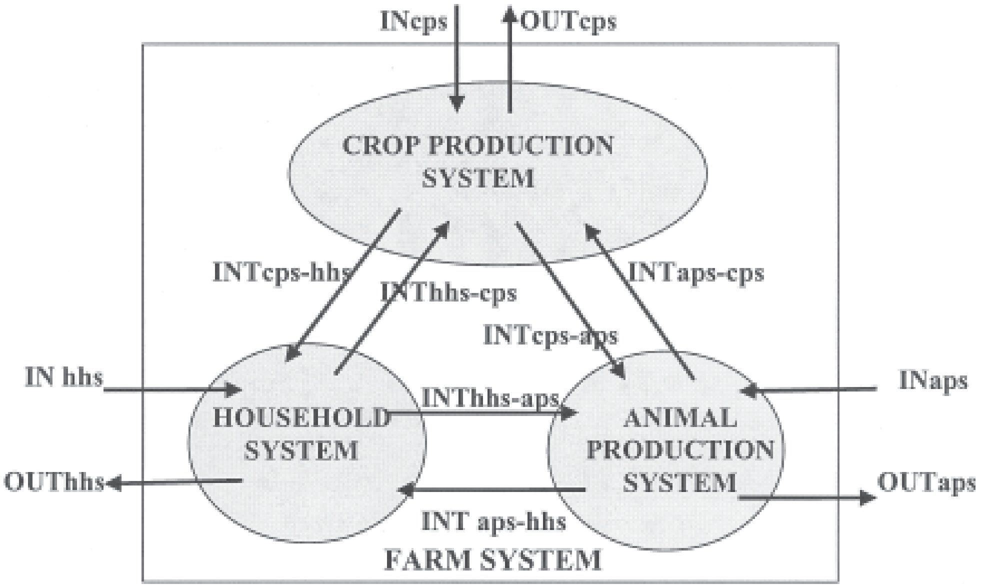


Figure 4. Nutrient Flows Within the Farming System (Defoer, 2003)

For each of the subsystems, the “visible flows” entering the farm from outside are presented as *IN*, and flows leaving the farm are presented as *OUT*. Links between the subsystems of the farm are presented as *INT* (“internal”).

The list below shows all possible types of flows, indicating which system each type belongs to (*cps*, *aps*, or *hhs*). For the internal flows, the link between the two subsystems of the farm is indicated.

IN*cps*	Flows entering the crop production system from outside the farm system.
OUT*cps*	Flows leaving the crop production system and farm system.
IN*aps*	Flows entering the animal production system from outside the farm system.
OUT*aps*	Flows leaving the animal production system and farm system.
IN*hhs*	Flows entering the household system from outside the farm system.
OUT*hhs*	Flows leaving the household system and farm system.
INT*cps-aps*	Flows from the crop production system to the animal production system.
INT*aps-cps*	Flows from the animal production system to the crop production system.
INT*cps-hhs*	Flows from the crop production system to the household system.
INT*hhs-cps*	Flows from the household system to the crop production system.
INT*aps-hhs*	Flows from the animal production system to the household system.
INT*hhs-aps*	Flows from the household system to the animal production system.

Nutrient flow analysis using this farm-level framework can be done "by hand" or using simulation models, such as the NUTMON model (Vlaming et al., 2001). The reader is referred to the DST guide for more details on NUTMON (Struif-Bontkes and Wopereis, 2003).

Nutrient flow analysis provides insight into the impact of farmer management decisions on soil fertility in his or her farm. Farmers transport material that contains nutrients: harvested products, manure, fertilizer, and straw used to build roofs. Some processes may lead to a loss in nutrients, e.g., burning of straw will result in complete loss of carbon and nitrogen. To compare flows, there is a need to express them in the same unit, e.g., kg of nitrogen, phosphorus, or potassium. This means that one needs to know the concentration of nitrogen in manure, millet grains, and millet straw, etc., and the amount of dry matter (at 0% moisture) that is produced, transformed, or transported.

Nutrient flow analysis tries to assist with questions such as: "What will happen to my soil if I do not apply any fertilizer to my rice field, and I sell both rice grain and rice straw?" It is important to realize that such analyses try to model a complex reality and should, therefore, be used with care. Boundaries of the farming system are analyzed and boundaries of its subsystems (e.g., rice production system, vegetable production system, animal production system, and household system) should be clearly defined. A negative nutrient balance may not be a reason for panic, because it does not tell us much about the sustainability of the system, unless one considers the stock of the particular nutrient in the soil. This nutrient stock to balance ratio is a better indicator of sustainability, because it gives an indication of how long a certain way of farming can continue without jeopardizing productivity and soil quality. However, it is also clear that productivity will start to decline long before the stock of nutrients is depleted. Nutrient stocks can be determined from laboratory analyses. Examples can be found in Defoer et al. (2000).

If nutrient flow analyses are done with farmers, it is important to realize that farmers do not think in terms of kilogram per hectare, but rather in terms of head loads, bags, cans, acres, plots of land, etc. It is important to use these terms as tools of analysis. Such discussions will, therefore, often be more qualitative than quantitative, but can still give important insights, pinpointing "leaks" in the system (e.g., unused animal manure, burning of straw).

6.2 Applications of the Farm-Level Framework

Adding Nutrients to Replenish Stocks and Flows (IN Flows)

Nutrient flows to the crop production system can enhance the soil nutrient supplying capacity. This can be achieved through fallowing, the application of mineral fertilizers and/or organic amendments, and cultivation of nitrogen-fixing crops. Natural processes such as wind deposition or deposition of sediments from water also enhance the soil nutrient supplying capacity.

The traditional practice of leaving land fallow is decreasing. Lack of land will often force farmers to move to fields that are less suitable for agriculture, leading to soil degradation in terms of soil nutrient supplying capacity and soil structure. Under natural fallow, an equilibrium content of SOM is reached related to inputs, rate of turnover, and capacity of the soil to retain SOM. Burning and opening up of the land will result in SOM decline to a new equilibrium related to reduced organic inputs, faster rate of turnover, and increased losses of SOM due to erosion. Fallows may be improved by introducing leguminous trees or herbs to capture nitrogen.

Wind deposition may add a substantial amount of nutrients in Sahelian production systems. Haefele (2001) estimated that up to 9 kg N, 0.2 kg P, 22 kg Ca, 15 kg Mg, 13 kg N, and 40 kg K per hectare and per year accumulate in double-cropped irrigated rice fields in the Senegal River valley as a result of dust deposition.

Use of mineral fertilizers usually requires growing a cash crop and well-organized factor (credit) and output markets. However, some success has also been obtained by spot-placing micro-doses of mineral fertilizers to traditional African cereals such as sorghum and millet. Mineral fertilizers are relatively expensive and farmers often lack knowledge of how best to apply them. Often the right type of fertilizer for the crop grown is not available, making fertilizer use very difficult. Farmers also need information on what to do if only limited quantities of mineral fertilizer can be bought.

Organic resources may be used to add nutrients, but in practice this is very difficult, because nutrient contents are low, especially for P. Soil P can be replenished with soluble P fertilizers, direct application of sufficiently reactive PR, or the combination of soluble P fertilizer and PR. In high P-sorbing soils, e.g., the red-clayey soils that cover about 25% of Africa’s soils, high levels of P addition may be required before a response is achieved. The residual benefits of such applications are potentially high. In sandier soils, lower applications may be given. However, the residual benefits will be limited, due to the combined effects of leaching of inorganic P and the limited existing fraction of organic P.

The suitability of PR for direct application to soil depends upon the mineralogy and reactivity of the PR, soil properties, climate, crop, and economics of use associated with the PR. Dissolution of PR requires low pH, low soil exchangeable Ca, and low soil solution P concentration (Buresh et al., 1997). Plants can enhance the dissolution of PR through acidification of the rhizosphere. A high P sorption capacity can promote more rapid dissolution of PR, but the low soil solution P concentration resulting from high P sorption may limit plant growth. Combined use of P fertilizers and legumes can result in synergism where nitrogen fixation can be enhanced because of reduction of P deficiency (Cassman et al., 1993).

Legumes may be used to boost the soil’s N supplying capacity. Fofana et al. (2004) demonstrated the beneficial effect of a mucuna short fallow on the yield of a succeeding maize crop. Nevertheless, a majority of N is often fixed in the grain. For example, the growing of soybeans may even result in a net removal of N from the field.

Reducing Non-Productive Nutrient Flows (OUT Flows)

Non-productive flows may include nutrient losses from the farming system through water or wind erosion, deep drainage, or gaseous losses. Some of the losses are better dealt with at field level (see Chapter 7). Losses are often especially important for nitrogen because of the dynamic nature of N cycling in the soil. There are three main forms of N “capital” in the soil: mineral N (ammonium NH_4 and nitrate NO_3), N in relatively labile soil organic matter, and N in a more stable form of soil organic matter (Giller et al., 1997). NH_4-N can be held as exchangeable cation or trapped as an interlayer cation in some 2:1 clay minerals, such as vermiculite and illite in vertisols. Under aerobic conditions, nitrifying bacteria quickly transform NH_4-N into NO_3-N (nitrification). Nitrate is highly mobile and easily lost by leaching or by denitrification (gaseous losses as NO, N_2O and N_2). Substantial losses of NH_4-N can also occur through volatilization (gaseous losses as NH_3), especially in alkaline soils.

Water and Wind Erosion

Water and wind erosion are major factors contributing to nutrient losses in Africa (Mando et al., 2001, Stroosnijder et al., 2001). Stoorvogel and Smaling (1990) have estimated annual erosion losses in low-input production systems of about 10 kg N ha^{-1}, 2 kg P ha^{-1}, and 6 kg K ha^{-1}. Such losses may be higher in case of high-input systems, or in case of high intensity rainfall. Water barriers, such as grass strips and stone rows, are effective options to reduce erosion (Kiepe et al., 2001; De Graaff, 1996; Mando et al., 2000; Zougmoré et al., 2000).

Erosion and runoff can also be reduced by a soil cover composed of living or dead biomass. These soil covers reduce water speed, avoid crust formation, and improve the soil's physical properties, such as porosity and saturated hydraulic conductivity rate (Mando and Stroosnijder, 1999). Soil cover has a non-linear effect; i.e., with a relatively thin soil cover, an important increase in water infiltration is obtained. Soil covers will also reduce evaporation losses. Roose (1994) and Lal (1974) showed that application of 2 tons ha^{-1} of straw led to a 60% reduction of runoff and 90% less erosion. With 6 tons ha^{-1}, runoff was reduced by 90% and erosion levels were reduced to zero. Leaving straw in the field leads also to significant reduction of the impact of wind erosion. In Niger, a 1.4 tons ha^{-1} millet straw cover reduced wind erosion losses by 63%.

Soil preparation methods may also be efficient in increasing infiltration and reducing runoff (Hoogmoed, 1999, Barro, 1999). A well-known example for crusted soils is the zai technique, where small pits are dug into the soil and small amounts of mineral and/or organic fertilizers are added.

Improving SOM content will generally reduce the susceptibility of the soil to form surface crusts and improves soil structure and water-holding capacity (Mando et al., 2001). SOM content can be improved through better crop residue management, rotations, and application of compost, manure, etc.

Leaching

Leaching of nutrients is especially important on sandy soils. Poss and Saragoni (1992) showed that N leaching accounted for 30%-85% of total urea-N losses under maize in Togo. Associated Ca and Mg losses varied with rainfall intensity and reached 115 kg Ca ha^{-1} and 30 kg Mg ha^{-1} yr^{-1}. Zougmoré et al. (2003) measured relatively low N leaching losses in a Lixisol under sorghum, i.e., about 39 kg ha^{-1} yr^{-1}, which were equivalent to 3%-14% of total N losses from the system. Godefroy et al. (1975) estimated that 50%-60% of K fertilizer applications in banana plantations in Côte d'Ivoire were lost through leaching.

Reducing deep drainage losses is difficult, but two approaches can be envisaged: (1) promoting root development by applying nutrients and improving soil structure. This will allow the crop to better profit from water infiltrated into the soil, and therefore reduce deep drainage; and (2) association of annual crops and trees. Trees will pump water and nutrients from below the rooting depth of annual crops, leading to better overall water and nutrient use (Huda and Ong, 1989).

Gaseous Losses

Denitrification and volatilization induce gaseous losses of N. Under anaerobic conditions, nitrate is reduced to N_2O and N_2 (denitrification). The best way to reduce denitrification is to improve soil drainage and maintain a good soil structure to avoid anaerobic growing conditions. Nitrogen volatilization as NH_3 is another important N loss mechanism. N losses through volatilization are important at high soil pH. They can reach 60% of N applied, especially in flooded rice fields. Volatilization can be reduced through deep placement of fertilizers, either by manual incorporation or injection. Nitrogen losses, through NH_3 volatilization during storage and handling of manure, limit its effectiveness as a nutrient source. Anaerobic storage in pits with or without addition of crop residues can significantly reduce N losses (Nzuma and Murwira, 2000).

Recycling (INT Flows)

Recycling through composting or animals improves the availability of nutrients. Nutrient release from manure or compost is much faster than from crop residues and is more in line with crop demand. It is, however, important to note that recycling of crop residues through animals also often results in nutrient losses (through urine) and carbon (respiration). The main constraint to the use of crop residues is competition for alternative use. The improvement of agronomic practices will usually result in the production of more biomass and therefore additional crop residues that can be used for multiple purposes.

Chapter 7. Field-Level ISFM Framework and Applications

As stated in Chapter 6, farmers may manipulate soil fertility in several ways. They may (1) add nutrients to replenish stocks and flows in the soil; (2) block nutrient flows leaving the farm ("leaks in the system"); (3) improve recycling nutrients that are not optimally used within the farm; or (4) increase the efficiency with which nutrients are used by the various production systems. The first three interventions were discussed in Chapter 6. In this section, the fourth option that farmers have is discussed in detail using a field-level ISFM framework.

The objective of this framework is to provide farmers with best-bet options to reach target values for yield and soil fertility, given crop management technology (choice of crop and variety, sowing date, crop establishment method, etc.), site (soil and weather conditions), input and output prices, and financial means of the farmer. The framework is largely based on theory developed for the QUEFTS model by Janssen et al. (1990). The reader is referred to the DST guide for more details on QUEFTS (Struif-Bontkes and Wopereis, 2003). A simplified version of the framework is first illustrated for a hypothetical irrigated rice crop. The full framework is then explained, followed by an example of how QUEFTS can be used to obtain site-specific nutrient management recommendations for rainfed maize in southern Togo.

7.1 Simplified Version of the Field-Level ISFM Framework

To estimate the fertilizer requirements for a given crop, three steps are necessary:

- Determine potential and target yield.
- Estimate the capacity of the soil to supply N, P, and K.
- Calculate fertilizer requirements.

Potential and Target Yields

The potential or maximum yield of a crop (Y_{max}) is determined by the climate (minimum and maximum temperatures and solar radiation), sowing date, and the characteristics of the variety chosen by the producer. For a given sowing date, Y_{max} is not constant but fluctuates from year to year because of climatic variability. Of course, the producer cannot change the weather, but he or she can choose a sowing date that will allow him or her to exploit the weather conditions more productively and to select a variety adapted to these conditions. Y_{max} can be obtained on experimental plots conducted under optimal growing conditions, where plant growth and development are not limited by factors other than solar radiation or temperature. Y_{max} is the real yield ceiling, limited by climate, sowing date, and varietal choice. In practice, this yield cannot be reached in farmers' fields, and it would also not be cost-effective. From an economical point of view, the maximum attainable yield, Y_a, is in the 70%-80% range of Y_{max}. The actual average farmer yield (Y_f) is often much lower because of several constraints that interfere with the rice crop, i.e., *growth limiting* factors such as lack of water and/or nutrient deficiencies and *growth reducing* factors, such as weed pressure, diseases, and pests. With optimal management, best farmer yields (Y_{bf}) can be considerably higher than Y_f. Yield gaps between Y_{max}, Y_a, Y_{bf}, and Y_f can be very important (Figure 5).

Farmers often achieve far less than $Y_{max.}$ It is, however, important to choose a realistic target yield. Yield increases of 0.5 or 1 t ha^{-1} compared to previously obtained yields are often possible in farmers' fields. The target yield should not be higher than the attainable yield (i.e., 70%-80% of Y_{max}). This is very important because crop response to nutrients is not linear from this point onward. Higher and higher fertilizer quantities are required to obtain the same increase in yield. This principle is illustrated for irrigated rice yields obtained as a function of fertilizer application rates in the Senegal River Valley (Figure 6). Targeting high yields is often neither economical nor realistic, especially when water management is not optimal (in such cases, the application of high quantities of fertilizer becomes too risky.)

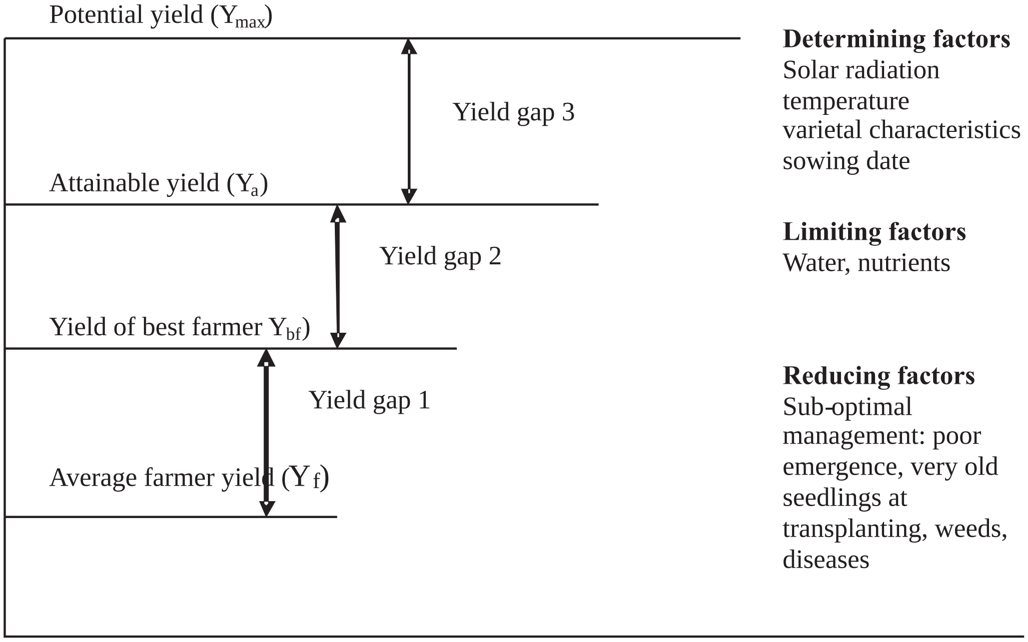


Figure 5. Yield Gaps Between the Average Yield (Y_f) in Farmers' Fields, the Yield of the Best Farmer (Y_{bf}), the Attainable Yield (Y_a), and the Potential Yield (Y_{max})

Estimate the Capacity of the Soil to Supply N, P, and K

The soil's capacity to supply N, P, and K nutrients can be estimated through chemical soil analysis. However, the relationship between these analytical data and crop growth is often poor, especially for N. A more direct method is to determine the soil nutrient supplying capacity through small, well-managed plots in farmers' fields that receive adequate quantities of fertilizer nutrients to reach the target yield, minus one nutrient (for instance, without N, P, or K). The yield obtained in these plots is considered an indicator of the soil's capacity to supply this "missing nutrient." The principle of these small zero-N, zero-P, and zero-K plots is explained in Table 4.

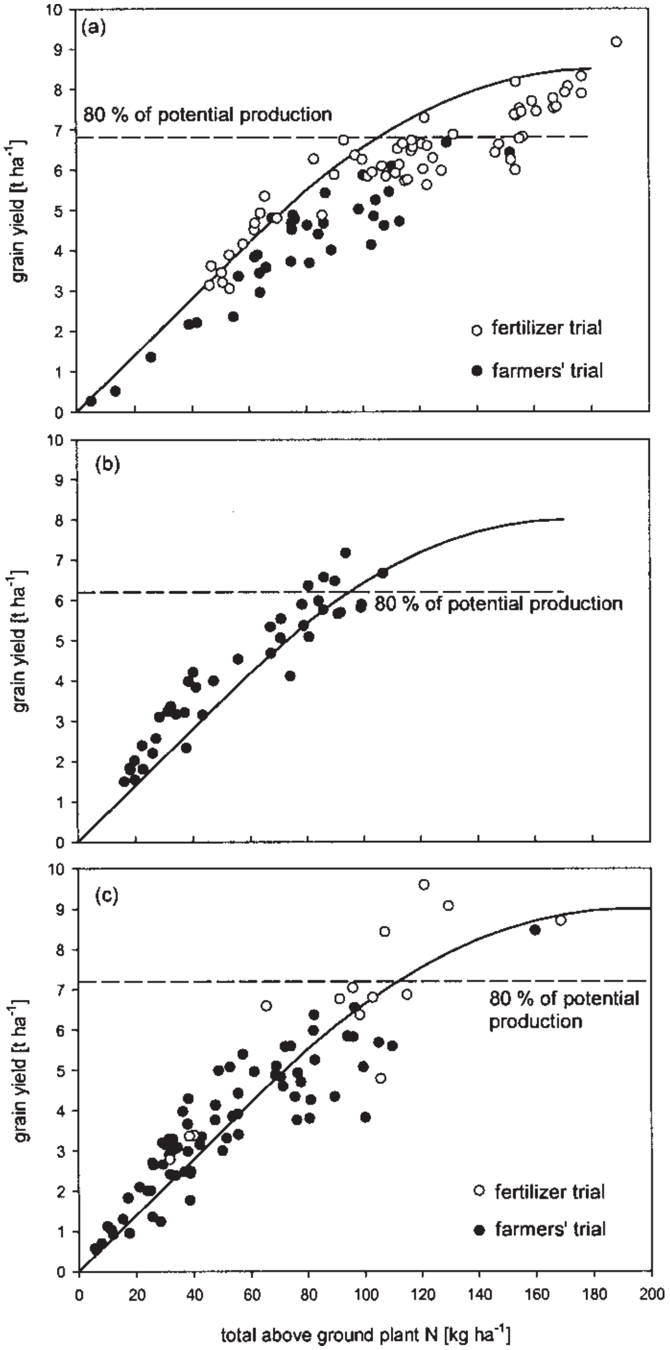
Figure 7 gives an example of the results obtained for these zero-nutrient plots. For the yield target, the soil nutrient supplying capacity is limiting in the order of N > P > K.

Calculating Fertilizer Requirements

We will illustrate this section by taking a hypothetical irrigated rice crop as an example. An example of nutrient contents for such a crop is given in Table 5. Nutrients leave the plot at harvest with the rice grains. Straw is often burned or incorporated in the soil. Using straw does not have much effect on the soil's capacity to supply P, nor N, but it increases K-supply. If the straw is not returned to the field, important quantities of K are lost to the system.

Field research in Asia and West Africa has determined optimal internal efficiencies for N, P, and K for rice (Haefele et al., 2003a and Witt et al., 1999). This work has shown that for a yield increase of 1 ton ha^{-1} and balanced N, P, and K nutrition, rice consumes (West Africa data only):

- 13 kg N ha^{-1}
- 2.5 kg P ha^{-1}
- 14 kg K ha^{-1}



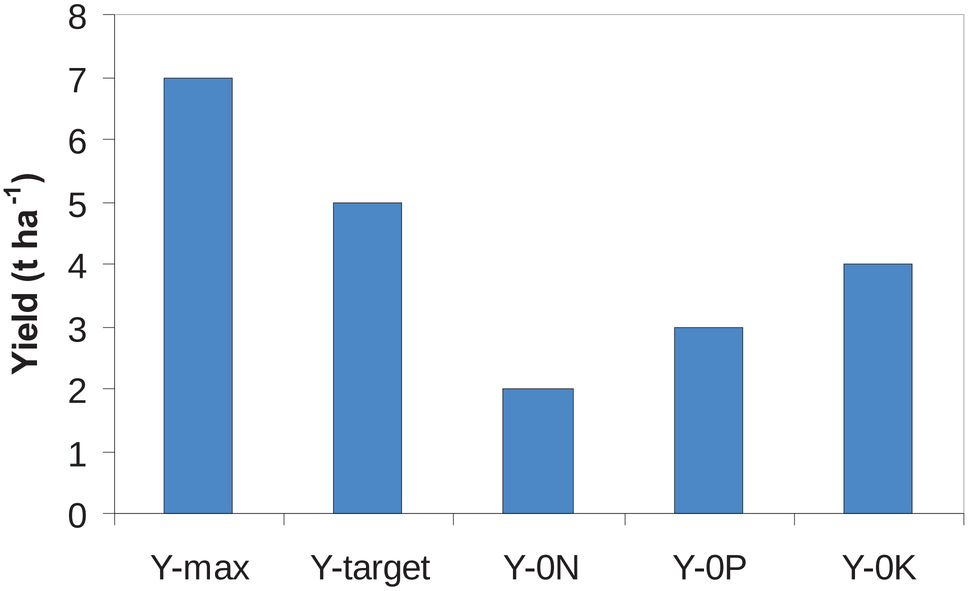
Closed symbols indicate data from farmers' fields (with and without fertilizer). Open symbols indicate data from fertilizer trials in farmers' fields. Solid line: simulated yield-N uptake curve. Dotted line: 80% of Y_{max}. (Haefele and Wopereis, 2004).

Figure 6. Relationship Between Irrigated Rice Grain Yield and Total N Uptake in Three Different Sites in the Senegal River Valley With Y_{max} = 8.5 tons ha^{-1} (a); Y_{max} = 8 tons ha^{-1} (b), and Y_{max} = 9 tons ha^{-1} (c)

Table 4. The Principle of Zero-N, Zero-P, and Zero-K Plots

Mini-Plots	N	P	K
Plot 0-N, +P, +K	0	+	+
Plot 0-P, +N, +K	+	0	+
Plot 0-K, +N, +P	+	+	0
Plot +N, +P, +K	+	+	+

0- = nutrient is not applied, it is the "missing nutrient;" + = nutrient is sufficiently applied to not limit crop growth (the exact amount will depend on the growth conditions). One may refer to recommendations currently used by extension staff or to what is done by the best farmer.



Y-max: potential yield; Y-target: target yield. Y-0N: yield obtained without N but with adequate doses of P and K. Y-0P: yield obtained without P but with adequate doses of N and K; Y-0K: yield obtained without K but with adequate doses of N and P.

Figure 7. Example of Yields Obtained in Zero-Nutrient Plots, Potential Yield, and Target Yield

Table 5. N, P, K Concentrations in Rice Grains and Straw. P and K Concentrations are Expressed in P_2O_5 and K_2O, Respectively; the Conversion Factor From P_2O_5 to P is 0.436 and From K_2O to K is 0.830

	N (%)	P_2O_5 (%)	K_2O (%)
Grain	1.0	0.4	0.3
Straw	0.5	0.2	1.5

Nitrogen

The recovery fraction of N (RFN, see Chapter 4) in a farmer's field is on average about 30%. This means that about 70% of N-fertilizer is lost because of many constraints, such as late urea application, weed pressure, seedlings that are too old at transplanting, etc. To obtain a balanced consumption of 13 kg N ha^{-1} for a yield increase of 1 ton ha^{-1}, one has to apply 43 kg N ha^{-1}, a little less than two bags of urea per hectare (because urea contains 46% N). Better field management can increase the recovery rate and diminish fertilizer losses. In the example of Figure 7, the yield of the 0-N plot is 2 tons ha^{-1}. To obtain the target yield of 5 tons ha^{-1}, one should apply about 130 kg N ha^{-1}.

It is better not to apply more than 50 kg N ha^{-1} at one time. The best timing for N-application in rice cropping is at the start of tillering, once rice seedlings have recovered from the transplanting shock, at panicle initiation, and at heading. For smaller quantities, it is advised to have two applications of 50% each at the start of tillering and at panicle initiation. For larger quantities, it is advised to apply in three splits: at the start of tillering (40%), at panicle initiation (40%), and at heading (20%). Fertilizer should not be applied in deep water (> 5 cm) or in weed-infested plots.

Phosphorus

The recovery fraction of P (RFP) is about 20% on average. Nevertheless, the phosphorus not absorbed by the crop generally remains available for the next year. In the first year, for a yield increase of 1 t ha^{-1}, (100/20)*2.5 = 12.5 kg P ha^{-1} will be required, i.e., about 29 kg P_2O_5 ha^{-1}, using 2.292 as the conversion factor to get units P_2O_5 from units P. This would be equivalent to (100/46)*29 = 63 kg TSP, because TSP contains about 46% P_2O_5.

Figure 7 shows that the yield of the 0-P-plot is 3 tons ha^{-1}. The target yield of 5 tons ha^{-1} can be obtained with an application of 58 kg P_2O_5 ha^{-1}. P application is preferably done as basal fertilizer. If not, it should be applied very early to stimulate tillering.

Potassium

The recovery fraction of K (RFK) is on average about 30%. As for phosphorus, the potassium not absorbed during the campaign is (normally) available the next year, although K is much more mobile than P, especially in relatively sandy soils. To cover the K requirement in the first year and to obtain a yield increase of 1 ton ha^{-1}, one should apply (100/30)*14 = 47 kg K ha^{-1}, thus 56 kg K_2O ha^{-1}, using 1.205 as the conversion factor to get units K_2O from units K. If the K fertilizer source is, e.g., K_2SO_4 containing about 50% K_2O, this would be equivalent to (100/50)*56 = 112 kg fertilizer.

The example of Figure 7 indicates that the yield of the 0-K plot is 4 tons ha^{-1}. To reach the target yield of 5 tons ha^{-1}, an application of 56 kg K_2O ha^{-1} is required.

K can be applied as basal fertilizer or as topdressing. Low quantities of K can be used at transplanting or as basal fertilizer. It is advisable to apply higher quantities (> 50 kg K_2O ha^{-1}) as basal fertilizer (50%) and at panicle initiation (50%).

Caution

These calculations are simplifications, because they do not allow for dilution or accumulation of plant nutrients or interaction between nutrients (see below). However, the small zero-N, zero-P, and zero-K plots are excellent soil fertility indicators. It is advisable to use them once every 3-5 years. Good management of these mini-plots is essential to ensure that the yields obtained actually express the capacity of the soil to supply the "missing nutrient." These well-managed mini-plots can become a means to evaluate the evolution of soil fertility in farmers' fields over time.

Caution is advised. Even if the yields of the small zero-nutrient plots do not indicate the need to apply fertilizer, it is possible that a maintenance application is necessary to prevent soil fertility from being mined over time. Using rice as an example, Table 5 estimates the requirements for a maintenance application. For instance, considering Figure 7, a target yield of 4 instead of 5 tons ha^{-1} does not require K application. Nevertheless, the soil loses a considerable quantity of K, especially when straw is exported from the plot. A rice grain yield of 4 tons ha^{-1} is usually equivalent to a straw yield of 4 tons ha^{-1}. This means that, with each harvest, the soil loses (Table 5) 4000*0.015 + 4000*0.003 = 72 kg K_2O ha^{-1}. Combining organic amendments and mineral fertilizers is often the best strategy to maintain or even increase soil fertility.

Table 6 gives optimal internal use efficiencies (IE_o in kg harvested product/kg nutrient uptake) for N, P, and K (balanced nutrition) for major crops in SSA. The reciprocal values are also indicated (kg nutrient uptake/ton harvested product). These figures can be used to convert grain yield determined in the field into nutrient uptake. Such relationships are valid up to the point where the yield target is about 70%-80% of the climate-adjusted potential yield (Y_{max}). Please note that when it is clear that a certain element is limiting, it is advisable not to use the figures from Table 6, but rather the values that are given in Table 7 for cases of maximum dilution.

7.2 The Field-Level ISFM Framework

The field-level ISFM framework is based on the QUEFTS model, which is illustrated in Figure 8.

The framework accounts for (adapted from Dobermann and Cassman, 2002, and Haefele et al. 2003a):

1. Regional and seasonal differences in yield potential.
2. Indigenous soil nutrient supplying capacity.
3. Uptake, recovery, and residual effects of fertilizer nutrients.
4. Relationship between nutrient uptake and yield formation.
5. Dynamics of nutrient demand during the cropping cycle (especially N).
6. Crop management practices (land preparation methods, crop establishment methods, etc.) and production system (crop rotations, associations).

Table 6. Approximate Values of Optimal Internal Use Efficiency for N (IEN_o), P (IEP_o) and K (IEK_o) for Different Crops (kg harvested product/kg nutrient uptake)

Relationships are valid up to the point where the yield target is about 70% to 80% of the climate-adjusted potential yield (Y_{max}). See Table 7 for details regarding literature sources for these data.

Crop	IEN_o	IEP_o	IEK_o	$1000/IEN_o$	$1000/IEP_o$	$1000/IEK_o$
	(kg/kg nutrient)			(kg nutrient/ton harvested product)		
Millet	34	145	18	29.4	6.9	55.6
Upland rice	45	743	48	22.2	1.3	20.8
Irrigated rice	75	407	71	13.3	2.5	14.1
Sorghum	38	278	42	26.3	3.6	23.8
Cassava	90	358	83	11.1	2.8	12.0
Groundnut	15	218	28	66.7	4.6	36
Maize*	60	192	75	16.7	5.2	13.3
Cotton	25	198	30	40	5.1	33.3

*For K the original data from the QUEFTS model are used, because Togolese data showed luxury consumption of K.

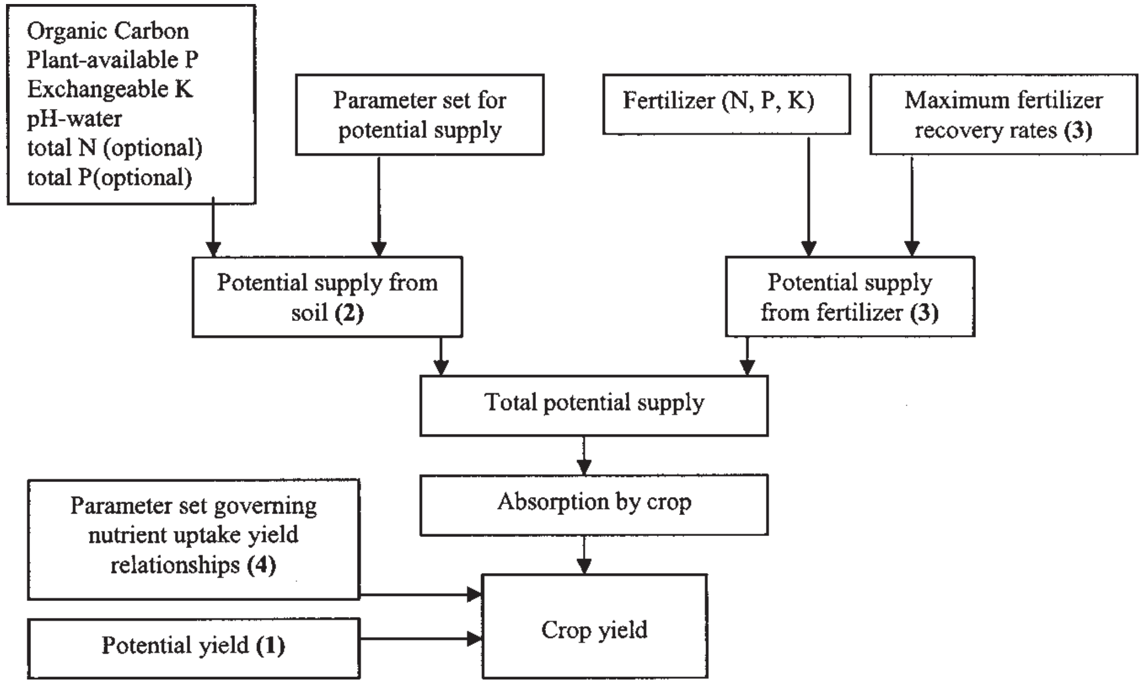


Figure 8. Basic Structure of the QUEFTS Model (From Struif-Bontkes and Wopereis, 2003). Numbers Between Brackets Refer to One of the Seven Points Covered in the ISFM Field-Level Framework.

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7. Local financial and risk considerations (prices of inputs, such as labor and fertilizer and produce prices; farmer purchasing power).

Points 1 to 4 and 7 are captured by the QUEFTS model (Janssen et al., 1990). All seven points are explained in more detail below.

1. Regional and Seasonal Differences in Yield Potential

Knowledge of the “yield ceiling” (Y_{max}) in a given growth environment is crucial because it determines the “upper limit” for nutrient uptake. In practice, farmers will not achieve this yield ceiling because it will not be economical to do so. The yield ceiling that can be obtained in a given environment depends on several factors. In general, the following agricultural production levels can be distinguished (e.g., Bouman et al., 2002), where yield-reducing factors, such as pests and diseases and weed interference, may occur at all levels:

- Potential production—Growth occurs in conditions with an ample supply of water and nutrients; growth rates are determined by varietal characteristics and weather conditions only (radiation and temperature).
- Water-limited production—Growth is limited by water shortage during at least part of the growing period; nutrients are in ample supply.
- Nutrient-limited production—Growth is limited by a shortage of nutrients during at least part of the growing season.
- Water and nutrient limited production—Growth is limited by a shortage of water and nutrients during at least part of the growing season.

Even under irrigated conditions, large variability may occur within a year as a function of sowing date and between years due to climatic variability. Dingkuhn and Sow (1997) illustrated the variability in yield potential for irrigated rice for a number of key irrigation schemes in the West African Sahel. In the Senegal River Valley, for the most commonly used sowing dates, potential rice yield varied from 8 to 9 t ha^{-1} in the wet season moving from the Senegal River Delta inland to Bakel (about 600 km further along the Senegal River). In the dry season, potential yield dropped more drastically, from 10 tons ha^{-1} in the Senegal River Delta to only 5-6 tons ha^{-1} near Bakel. There was also huge yield variability as a function of sowing date because of problems with cold in the wet season and heat in the dry season. In the wet season, rice yield was almost zero, if sowing occurred as late as September. Obviously, knowledge of such regional and seasonal differences in yield potential is of great importance to nutrient management. The same level of nutrient uptake results in very different yields, depending on the yield potential (i.e., yield ceiling), see Figure 6.

Under rainfed conditions, water availability is a function of rainfall, redistribution of rainwater by runoff and run-on, and losses by evaporation and leaching. Given the low inherent soil fertility of most African soils, soil nutrient status rather than soil water availability will often limit crop production. However, in areas where soils are shallow, with low water storage capacity, or where rainfall cannot penetrate into the soil (e.g., because of crusting), water can be severely limiting growth even at relatively high levels of annual rainfall because water cannot be used by the crop. Good results will usually be obtained by combining water harvesting techniques (e.g., breaking the crust and blocking runoff to let water infiltrate into the root zone) and improved soil fertility management (organic fertilizers in combination with mineral fertilizer in micro-doses).

In areas with relatively good soil fertility, such as floodplains and inland valley lowlands, lack of water control may cause drought or flooding to limit growth. In such cases simple water control measures, such as bunding may reduce risk and give an incentive to increase production through improved soil fertility management.

In principle, crop simulation models could help determine yield potential for the four production situations. However, very few simulation models exist that can handle all four production situations defined above. For rice, the ORYZA2000 crop growth simulation model (Bouman et al., 2002) simulates all four situations, if nitrogen is the only nutrient considered. The model cannot handle limitations of nutrients other than nitrogen and is not validated for situations where water and nitrogen are both limiting. For rice, the ORYZA2000 model has been adapted for Sahelian irrigated growth situations (Dingkuhn and Sow, 1997) but not for water-limited conditions. In other words, the model cannot readily be applied for rainfed rice conditions in SSA. For maize, the CERES-DSSAT model (Jones et al., 1998) has been validated for combined water-limited conditions in Togo (Dzotsi et al., 2003). If no crop simulation models are available or data to run such models are lacking, yields of best farmers or from experimental stations can serve as a proxy for potential yield.

2. Indigenous Soil Nutrient Supplying Capacity

Knowledge of the soil nutrient supplying capacity is crucial to site-specific ISFM, especially if the use of external inputs is limited (Haefele et al., 2003a). Soil tests exist that permit estimation of soil nutrient supplying capacity. The original version of QUEFTS (depicted in Figure 8) uses “pedotransfer functions” to convert such soil parameters obtained in the laboratory (such as organic C and pH) into nutrient availability for the crop. However, these are often rather unreliable and not within reach of the average farmer in SSA. For example, for lowland rice, no good soil tests exist to determine indigenous nitrogen supply (Dobermann et al., 2002). An alternative is to determine soil nutrient supplying capacity through small nutrient-omission plots, where the nutrient of interest is deliberately not applied. The soil nutrient supplying capacity is then estimated from crop nutrient uptake in that particular plot. Wopereis et al. (1999) and Witt et al. (1999) provide successful examples of this approach. Soil nutrient supplying capacity varies widely among fields and seasons and is often related to soil organic matter content, although no clear relationship could be established for irrigated lowland rice fields (Cassman et al., 1996). Farmers could rely on such small nutrient omission plots (and move them every year to another location to avoid prolonged soil nutrient depletion) to guide fertilizer applications before crop emergence (especially P and K fertilizers). Adapted versions of QUEFTS exist that allow users to input data directly from nutrient omission plots instead of soil test data (e.g., Haefele et al., 2003a).

In northern Togo, nutrient-omission trials identified N as the nutrient most limiting maize yield on compound fields and outlying fields. The compound fields benefited from long-term organic fertilizer inputs close to the family homestead. The outlying fields received considerably less or no organic fertilizer inputs. Soil organic C content was 13.4 g kg^{-1} for compound fields and 6.3 g kg^{-1} for outlying fields. This very large difference in soil fertility meant that maize yields on compound fields were consistently 1.0 to 1.5 tons ha^{-1} higher than on outlying fields. The current blanket recommendation for maize in northern Togo places great emphasis on P. This is unnecessary and especially wasteful of resources on compound fields, which contain large amounts of available P, as observed through the nutrient-omission plots and through conventional laboratory analyses. Such observations are now being picked up by farmers (Wopereis et al., 2005).

3. Uptake, Recovery, and Residual Effects of Fertilizer Nutrients

Recovery of fertilizer nutrients is key to ISFM. Nutrient recovery may be enhanced through improved crop and resource management. Synchronization of plant demand for nutrients and fertilizer application may greatly enhance recovery. Better management of yield-reducing factors like soil acidity, soil salinity, weeds, pests, and diseases may increase nutrient recovery from fertilizers. Fertilizer applications targeted at the right, growth-limiting nutrients and placed near the roots may greatly enhance crop performance. Mulching (e.g., with rice straw or mucuna residues) may conserve moisture and smother out weeds, enabling better crop establishment and nutrient uptake. Water management is of great importance because nutrient availability for plants will depend to a large extent on water availability.

For rice, extensive knowledge is available on average recovery of N, P, and K in West Africa (Wopereis et al., 1999; Haefele et al., 2003b) and Asia (Witt et al., 1999). Not much knowledge is available on the recovery and residual effect of nutrients applied through organic amendments (manure, compost) and phosphate rock.

Combined use of mineral fertilizers and organic amendments affects the indigenous soil nutrient supplying capacity (including residual effects). This may also affect recovery of fertilizer nutrients and internal nutrient efficiency (by addressing other yield limiting factors, e.g., other nutrients, water stress, etc.). Input parameters for QUEFTS can be adjusted accordingly to allow for such synergetic effects. If the indigenous soil nutrient supplying capacity is improved over time, recovery of nutrients from mineral sources may decline because of declining returns to nutrient uptake as yields approach the yield ceiling.

In northern Togo, average recovery fractions of applied N fertilizer (RFN) were indeed significantly ($p = 0.01$) higher on compound fields as compared to outlying fields over 3 years (0.41 versus 0.33 kg kg^{-1}). However, the agronomic efficiency of applied N (AEN) was similar over 3 years (19.0 kg grain kg^{-1} N), comparing favorably to the relative cost of N fertilizer (4 kg grain kg^{-1} N). The greatest differences between outlying and compound fields were observed in 2001, due to low and erratic rainfall. This points at an indirect interaction: improved soil moisture supply on compound fields as compared to outlying fields (Wopereis et al., 2005).

The mulching effect of a mucuna short fallow in southern Togo led to increased fertilizer N recovery in the succeeding maize crop. The best fertilizer N recovery rate of 56% was obtained at modest N application rates (50 kg N ha^{-1}), with a preceding mucuna short fallow and with 40 kg P ha^{-1} (Fofana et al., 2004).

Fertilizer N recovery rates observed in a maize-Acacia system in southern Benin were very low (ranging from 10% without trees to 17% with trees) and seemed to indicate that too much N was applied (Toose et al., 2005).

4. Relationship Between Nutrient Uptake and Yield Formation

The relationship between nutrient uptake and rice yield (the internal nutrient use efficiency) is not linear. Janssen et al. (1990) used two linear envelope curves to describe maximum accumulation and maximum dilution for nutrients to reach a particular yield level and used these to derive linear-parabolic yield curves as a function of nutrient uptake (N, P, and K in the present version of QUEFTS). Envelope curves for rice were developed by Witt et al. (1999) for Southeast Asia and by Haefele et al. (2003a) for West Africa. Results were remarkably similar. Work has begun to derive similar envelope curves for maize in SSA as illustrated in Figures 9A to C. Dobermann and Cassman (2002) have already published such curves for maize systems in the United States.

Janssen (2003) derived the envelope curves for a number of crops that are cultivated in SSA (Table 7) and these data can be readily used in the QUEFTS model.

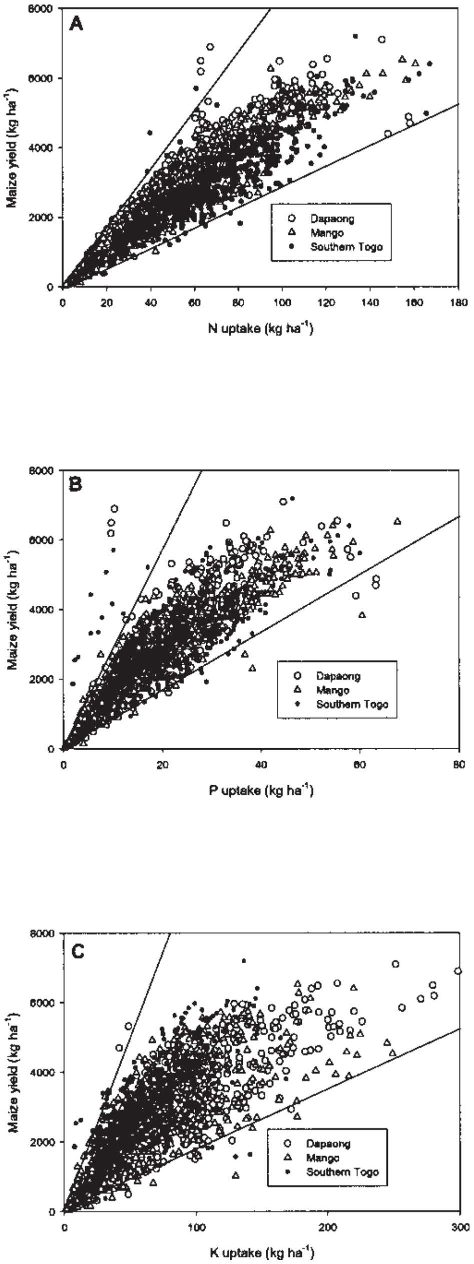

Figure 9. Maize Yield as a Function of Nutrient Uptake (A: Nitrogen; B: Phosphorus; C: Potassium) in Northern Togo (Dapaong, Mango) and Southern Togo (1200 data points). Lines Indicate Maximum Accumulation and Dilution of N, P, and K.

The variability in internal efficiency of N (IEN, see Chapter 4) is shown in Figure 9A. If other elements are limiting growth (e.g., P or K, or drought), internal N efficiency is relatively low and close to the line of maximum accumulation. IEN is enhanced if such limiting factors are dealt with through better crop management. IEN in general is also influenced by the choice of crop or cultivar. Farmers often match differences in nutrient requirements of their crops to soil fertility levels in their fields. For example, nutrient demanding crops like maize are usually found near the homestead. Local cultivars may perform better without inputs than improved varieties, while improved varieties perform better in a favorable environment with inputs. Similarly, sowing time and sowing density affect yield potential and hence IEN.

The yield a farmer will obtain depends on quantities of nutrients that are taken up by the plant, either from the soil or from fertilizer sources. If this nutrient uptake is balanced (i.e., neither excessive dilution nor accumulation of nutrients occur), then a whole range of other factors intervene as well. Most notable of these factors are variability in weather and choice of crop management practices, such as sowing date, variety, weed management strategies, etc. Looking beyond a growing season, it is important to know whether application of soil amendments will have a "lasting" effect, i.e., will contribute to soil organic matter build-up. Will this eventually lead to increased soil nutrient supplying capacity, improved recovery of fertilizer nutrients, or whether it mainly acts as a mineral fertilizer, i.e., a one-time boost to crop growth?

5. Dynamics of Nutrient Demand During the Cropping Cycle (Especially N)

This aspect is not dealt with in the QUEFTS model. For most crops, the dynamics of demand for nutrients during the cropping cycle are well known. For rice, N application is needed at mid-tillering to boost tillering

Table 7. Approximate Values of Ratios of Yield to Uptake at Maximum Dilution and at Maximum Accumulation (kg harvested product/kg nutrient uptake)

Crop	N	P	K	Region	Source
		maximum dilution			
Millet	60	250	30	Mali	Samake et al. (2004)
Upland rice	65	1200	70	Côte d'Ivoire	Koopmans (1990)
Irrigated rice	112	586	102	West Africa	Haefele et al. (2003b)
Sorghum	65	470	65	General	Wolf (1984), Nijhof (1987)
Cassava	145	590	135	General	Wolf (1984), Nijhof (1987)
Groundnut	20	340	45	General	Wolf (1984), Nijhof (1987)
Maize	88	296	120	N. Togo	Janssen (2003)*
Cotton	30	360	50	General	Wolf (1984), Nijhof (1987)
		maximum accumulation			
Millet	7	40	5	Mali	Samake et al. (2004)
Upland rice	25	285	25	Côte d'Ivoire	Koopmans (1990)
Irrigated rice	48	211	32	West Africa	Haefele et al. (2003b)
Sorghum	10	85	18	General	Wolf (1984), Nijhof (1987)
Cassava	35	125	30	General	Wolf (1984), Nijhof (1987)
Groundnut	10	95	10	General	Wolf (1984), Nijhof (1987)
Maize	32	88	18	N. Togo	Janssen (2003) *
Cotton	10	35	10	General	Wolf (1984), Nijhof (1987)

*For K the original data from the QUEFTS model are used, because Togolese data showed luxury consumption of K.

Source: Janssen (2003).

(horizontal growth), panicle initiation (vertical growth), and near booting (grain filling). Simulation models exist that can predict rice phenology as a function of sowing date and weather data, e.g., ORYZAS (Dingkuhn and Sow, 1997) and RIDEV (Dingkuhn, 1997). Such models can, therefore, guide farmers with optimal application dates for N. In practice, farmers will rely on expert knowledge for information on best timing of nutrient applications. Well-timed fertilizer applications will have a substantial beneficial effect on recovery of fertilizer nutrients by the crop.

6. Crop Management Practices (Land Preparation Methods, Crop Establishment Methods, Soil and Water Management, etc.), and Production System (Crop Rotations, Associations)

Crop management practices other than soil fertility management can determine to a large extent how effective ISFM is in practice. Neglected weed management is just one typical example. ISFM recommendations need to take peculiarities of crop management and production systems (e.g., maize-cassava associations) into account. Ultimately ISFM recommendations should be developed that are specific for given crop management and production systems.

7. Local Financial and Risk Considerations (Prices of Inputs, Such as Labor and Fertilizer Prices and Prices of Produce; Farmer Purchasing Power)

Recommendations need to be based on the socioeconomic context (input and output prices) and allow for differences in farmer purchasing power. For example, if farmers can only afford to buy one bag of fertilizer, advice should be available to guide them about what to buy. Examples of how this can be done have been given by Haefele and Wopereis (2004) and in Section 7.3 below.

7.3 Applications

The use of the field-level ISFM framework and QUEFTS is illustrated with the example of the village of Djaka Kopé, southern Togo. Twenty farmers installed small nutrient-omission plots in part of their fields on “terre de barre” soil during the main rainy season in 2003. Some fields had profited from a mucuna short fallow during the preceding short rainy season in 2002; others had not. Results for maize yield are shown in Table 8.

From the table it is clear that K is the element most limiting maize yield in the area. There is also a strong beneficial effect from inclusion of mucuna in the production system in this region, especially on the capacity of the soil to supply N and P.

Suppose we would like to determine best-bet soil fertility management options for maize as a function of target yield, without and with a mucuna short fallow, assuming recovery rates of 0.3 kg kg^{-1} for N, 0.5 kg kg^{-1} for P, and 0.5 kg kg^{-1} for K and a yield ceiling of 6 tons ha^{-1}. We used the QUEFTS model to conduct the necessary calculations for target yields between 1 and 5 tons ha^{-1}, with incremental steps of 1 ton ha^{-1}. The assumption is

Table 8. Maize Yields and Nutrient Uptake Obtained in Nutrient-Omission Plots Installed in Farmers’ Fields With a Preceding Mucuna Short Fallow (11 Farmers) and Without a Preceding Mucuna Short Fallow (9 Farmers)

Treatments	With Mucuna (t/ha)		Without Mucuna (t/ha)	
	Yield	Nutrient Uptake	Yield	Nutrient Uptake
	(kg ha^{-1})	(kg ha^{-1})	(kg ha^{-1})	(kg ha^{-1})
N	2,504	46.9 kg N ha^{-1}	1,240	28.6 kg N ha^{-1}
P	2,378	7.4 kg P ha^{-1}	1,264	4.8 kg P ha^{-1}
K	1,394	7.4 kg K ha^{-1}	1,120	8.8 kg K ha^{-1}

that farmers have access to urea (containing 46% N), triple superphosphate (TSP, containing 46% P_2O_5) and K_2SO_4 (containing 50% K_2O) mineral fertilizers. Results of QUEFTS simulations conducted for maize without a preceding mucuna short fallow are shown in Table 9 and for maize that profited from a preceding mucuna short fallow in Table 10.

The beneficial effect of the preceding mucuna short fallow is clearly visible in the results. With a mucuna short fallow, urea application is needed only if farmers target yields of 3 tons ha^{-1} and higher. As mentioned earlier, target yields should generally not exceed 70%-80% of potential yield. In this case, it would be advisable to target yields that do not exceed 4 tons ha^{-1}.

Table 9. QUEFTS Simulations for Maize Target Yields From 1 to 6 tons ha^{-1} Without a Preceding Mucuna Short Fallow

Nutrient input needs and fertilizer needs are calculated, assuming recovery fractions of 30% for N, 40% for P, and 50% for K. Potential yield set to 6 tons ha^{-1}.

Y Target	N Needs	P Needs	K Needs	Fertilizer N	Fertilizer P	Fertilizer K	Urea	TSP	K_2SO_4
(ton ha^{-1})	kg ha^{-1}						(number of bags ha^{-1})		
1	0	0.2	4.7	0.0	0.5	9.4	0.0	0.1	0.4
2	8.6	7.4	24.5	28.7	18.5	49.0	1.2	1.9	2.3
3	27.1	13.5	41.2	90.3	33.8	82.4	3.9	3.4	3.9
4	47.8	20.3	59.7	159.3	50.8	119.4	6.9	5.1	5.7
5	79.8	30.8	88.4	266.0	77.0	176.8	11.6	7.7	8.4

Table 10. QUEFTS Simulations for Maize Target Yields From 1 to 6 t ha^{-1} With a Preceding Mucuna Short Fallow

Nutrient input needs and fertilizer needs are calculated, assuming recovery fractions of 30% for N, 40% for P, and 50% for K. Potential yield set to 6 t ha^{-1}.

Y Target	N Needs	P Needs	K Needs	Fertilizer N	Fertilizer P	Fertilizer K	Urea	TSP	K_2SO_4
(ton ha^{-1})	kg ha^{-1}						(number of bags ha^{-1})		
1	0	0	2.2	0.0	0.0	4.4	0.0	0.0	0.2
2	0	3.5	21.8	0.0	8.8	43.6	0.0	0.9	2.1
3	8.8	10.9	42.6	29.3	27.3	85.2	1.3	2.7	4.1
4	29.5	17.7	61.1	98.3	44.3	122.2	4.3	4.4	5.8
5	61.5	28.2	89.8	205.0	70.5	179.6	8.9	7.1	8.6

The above calculations used points 1 to 4 of the ISFM framework. The calculations assumed no synergy between organic amendments and mineral fertilizers, i.e., nutrient recoveries (point 3) and internal nutrient efficiencies (point 4) were assumed to be the same for the situation with and without mucuna short fallow. If such effects were known, adjustment could be made in the input parameters for the QUEFTS model.

To improve N recovery, timing of N applications is crucial (point 5). Validation of the ISFM options should keep track of general crop management in farmers' fields, because differences may greatly affect results (point 6). A financial and risk analysis is clearly still needed (point 7) by, e.g., determining the value:cost ratios of mineral fertilizer use and comparing the benefits of a maize-mucuna short fallow rotation with a maize-cassava association.

Chapter 8. Conclusions

This guide reviews major agroecological principles to ISFM and introduces two frameworks, one at farm level and one at field level to help analyze soil fertility management strategies. It is meant for change agents from national research and extension agencies, from NGOs and from development projects involved in agricultural research and development. We hope that this guide, in combination with the DST guide published in 2003 by CTA and IFDC (Struif-Bontkes and Wopereis, 2003) will help users to develop “systems skills” to decipher the complexity of plant responses to climate, soil fertility, and management decisions such as sowing date, use of organic inputs, fertilizer management, etc. This will hopefully allow turning “blanket soil fertility management recommendations” into recommendations specific for sowing date, soil type and available organic inputs, and mineral fertilizers.

Systems skills, however, are not sufficient. In addition, participatory research and extension skills are important to (1) build bridges between farmer and outside (scientific) knowledge; (2) build partnerships along commodity chains to facilitate access to input and output markets; and (3) ensure ownership and understanding at farmer-level of innovations, which will facilitate scaling-up and -out through farmer-to-farmer extension. It is a matter of seeing the whole picture, while using “new” tools. This clearly calls for new curricula development in SSA both at the university and agricultural school levels.

We sincerely hope that this guide on agroecological principles of ISFM will enhance the relevancy of on-farm research in SSA. This should enable farmers to gradually adopt more site and season-specific nutrient management, ultimately leading to enhanced and more sustainable agricultural production.

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