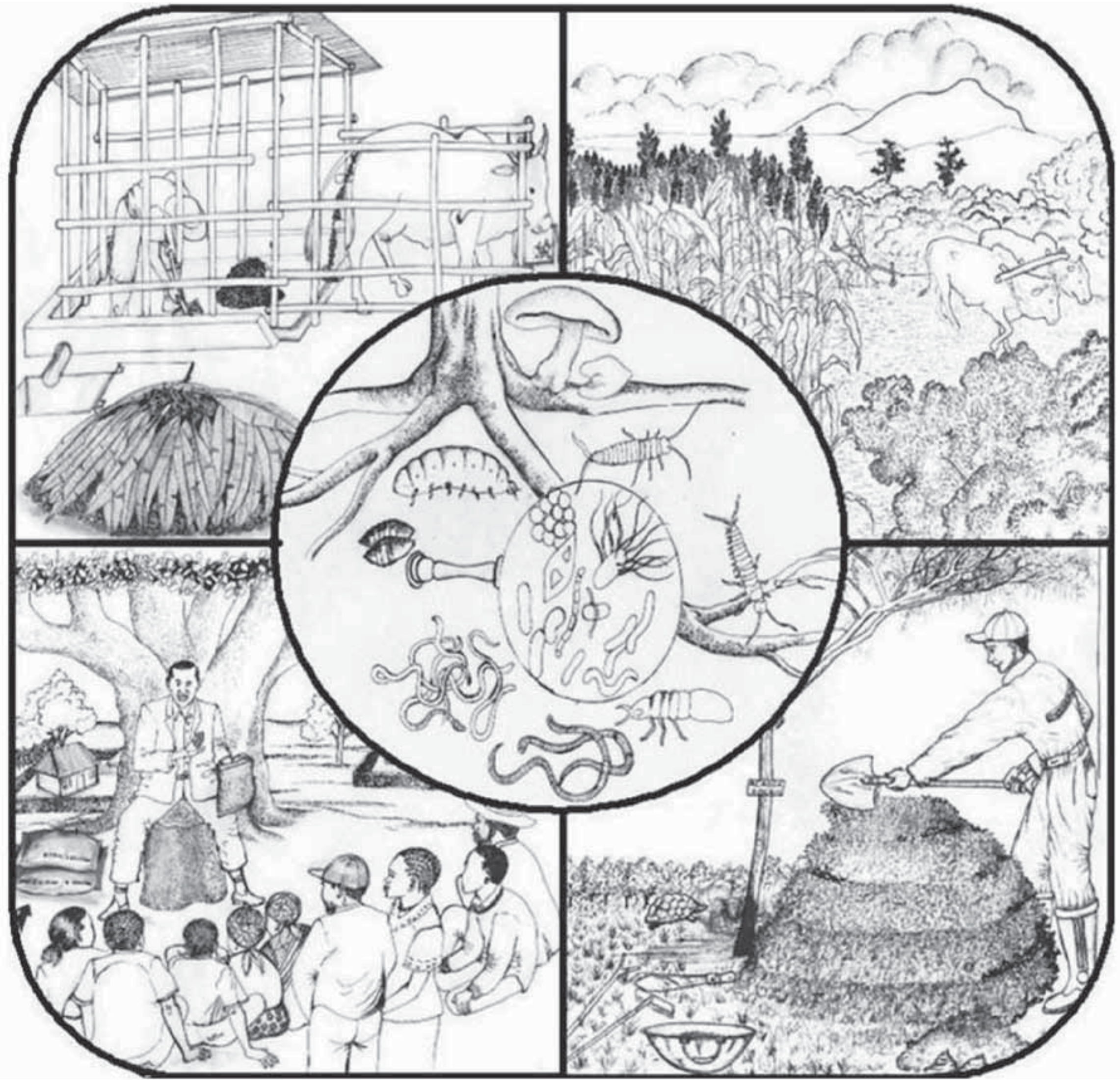
Part I

Principles of ISFM



Chapter 1. ISFM as a strategic goal

Integrated Soil Fertility Management (ISFM) may be defined as *'the application of soil fertility management practices, and the knowledge to adapt these to local conditions, which maximize fertilizer and organic resource use efficiency and crop productivity. These practices necessarily include appropriate fertilizer and organic input management in combination with the utilization of improved germplasm.'* ISFM is not characterized by unique field practices, but is rather a fresh approach to combining available technologies in a manner that preserves soil quality while promoting its productivity. ISFM practitioners do not merely recite this definition, but plan much of their annual field activities around it. Soil fertility management includes timely and judicious utilization of pre-plant and top-dressed mineral fertilizers, but also the generation, collection, storage, enrichment and application of available organic resources and the maintenance and enhancement of beneficial soil organisms and biological processes.

ISFM is a response by land managers who recognize that soil degradation and nutrient depletion pose a serious threat to rural wellbeing and it involves a series of informed management decisions that require in-depth understanding of available resources and their alternative uses, responsive field actions throughout the year, continuous assessment of their effects and early preparation for future actions. ISFM practitioners are also promoters within their local communities because land conservation and better farming are among their favorite topics of conversation, and they seek to exchange experiences with their friends and neighbors in a helpful manner. In its fullest context, ISFM is not an arsenal of silver bullets targeted by land managers in all circumstances and locations, rather it is a compass that points them toward better land stewardship and rural livelihood.

Current smallholder practice in Africa is too often abusive, mining the soil of its nutrients and leading to degraded, non-productive farming (Smaling *et al.* 1997). Simply introducing improved crop varieties and modest amounts of mineral fertilizer may improve crop yields but at a relatively low agronomic efficiency (AE) of nutrient use. Combining fertilizer addition with locally-available organic inputs while retaining or enriching crop residues improves nutrient use efficiency and protects soil quality. Thus, several intermediary phases may be identified along the progression from farmer current practice toward optimized ISFM (Figure 1.1). Complete ISFM comprises the use of improved germplasm, fertilizer, appropriate organic resource management and adaptations to local conditions and seasonal events. These adjustments lead to specific management practices and investment choices, and are iterative in nature leading to better judgments by farmers concerning weed management, targeting of fertilizer and organic resources and preference of crop varieties.

Farmer resource endowment also influences ISFM, as do market conditions and favorable policies promoting farm input supply. Local adaptation also adjusts for variability in soil fertility status and recognizes that substantial improvements in the AE of applied nutrients may be expected on more responsive soils (A in Figure 1.1). On poor, less-responsive soils, application of fertilizer alone may not result in improved nutrient use (B in Figure 1.1) and fertilizer is better applied in combination with organic resources (C in Figure 1.1). Additions of organic material to the soil provide several mechanisms for improved AE, particularly increased retention of soil nutrients and water and better synchronization of nutrient supply with crop demand, but it also improves soil health through increased soil biodiversity and carbon stocks. ISFM is effective over a wide range of fertilizer application rates and can greatly improve the economic returns from investments in modest farm inputs by small-scale farmers. ISFM also deters land managers from applying fertilizers at excessive rates that result in reduced AE and environmental pollution.

Mineral fertilizers are important within ISFM, but not as a standalone means to crop nutrient management. Within responsive soils, fertilizer is indeed a valid entry point for ISFM, while in the poorest soils organic resource management options must be implemented in conjunction with mineral fertilizer addition before sufficient crop responses are realized. This situation holds true

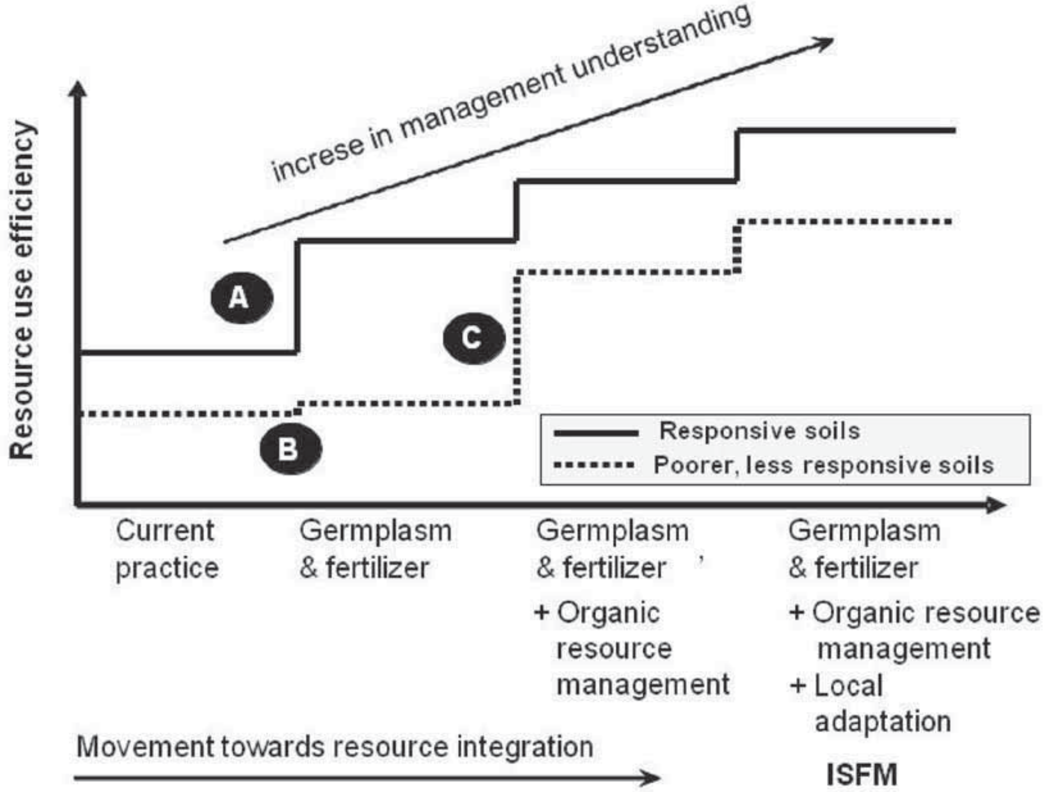


Figure 1.1. Conceptual relationship between the efficient use of resources as one moves from current practice to achieve ISFM.

under a number of soil conditions including shallow or sandy soils, degraded soils with collapsed physical structure and low soil organic matter and in highly weathered soils with toxic properties.

ISFM practice assists in overcoming a wide range of crop constraints, including those not directly related to nutrient supply. For example, the use of crop residues as surface mulch not only releases mineralized nutrients over time but also reduces soil moisture loss and resists erosion. Similarly, the construction of water harvesting structures in semi-arid areas improves nutrient use efficiency as well as increases available moisture. ISFM is particularly appropriate when employed in conjunction with less than optimal rates of fertilizer addition through its improvement of AE and supplementation by organic resources, as illustrated through the succession of paradigms governing soil fertility management in the tropics (Table 1.1), ISFM also embraces a suite of conditions that foster its adoption, such as greater access to farm input supplies, fairer commodity markets and conducive regulatory and trade policies.

Fertilizer as an entry point for ISFM

The recommendation of the African Fertilizer Summit (2006) *'to increase the fertilizer use from the current 8 to 50 kg ha^{-1} nutrients by 2015'* reinforces the role of fertilizer as a key entry point for increasing crop productivity and attaining food security and rural well being in SSA. The impact of this target will, however, vary depending upon the agronomic efficiency of applied fertilizer, defined as *'the amount of output (e.g. crop yield) obtained per unit of fertilizer applied'*. This efficiency varies across regions, countries, farms, and fields within farms and greatly affects the returns to the recommended 50 kg ha^{-1} (Prudencio 1993; Manlay *et al.* 2002; Samake *et al.* 2005). Generally on responsive soils, where applied fertilizer nutrients overcome crop nutrient limitations, substantial

Table 1.1 Changes in tropical soil fertility management paradigms and their effects on farm resource management over the past five decades (after Vanlauwe *et al.* 2006).

Period	Paradigm	Role of fertilizer	Role of organic inputs	Experiences
1960s and 1970s	1st External Input Paradigm	Use of fertilizer alone will improve and sustain yields.	Organic resources play a minimal role.	Limited success due to shortfalls in, supply infrastructure, policy and adoption.
1980s	Organic Input Paradigm	Fertilizer plays a minimal role in land quality maintenance.	Organic resources are the main source of nutrients and substrate.	Limited adoption as organic matter production requires excessive land and labor.
1990s	Sanchez' s Second Paradigm	Fertilizer use is essential to alleviate the main nutrient constraints.	Organic resources serves as an entry point offering functions other than nutrient release.	Difficulties to access organic resources hampered adoption (e.g. improved fallows).
2000s	Integrated Soil Fertility Management	Fertilizer is a major entry point to increase yields and supply needed organic resources.	Access to organic resources has social and economic dimensions.	On-going as described in this book.

responses to fertilizer can be expected (Vanlauwe *et al.* 2006). On less-responsive soils where other constraints are limiting crop growth, fertilizer alone in absence of other corrective measures results in relatively low AEs and small improvement in crop yield (Carsky *et al.* 1998; Zingore *et al.* 2007a). Also important is the heterogeneity that exists between households within a community, resulting in differing production objectives and resource endowments (Tittonell *et al.* 2005a; Giller *et al.* 2006). The above factors co-determine the range of soil fertility management options available to the household. Ojiem *et al.* (2006) derived the concept of the 'socio-ecological niche' for targeting ISFM technologies, which adjusts for local social, economic and agro-ecological conditions but requires detailed understanding before it can be applied to individual farms (see Chapter 15).

Fertilizer not only improves crop yields but it also increases the quantity of available crop residues useful as livestock feed or organic inputs to the soil (Bationo *et al.* 2004). Targeting phosphorus (P) application to legumes doubles crop biomass and increases the fertilizer AE of the following cereal crop (Vanlauwe *et al.* 2003; Giller *et al.* 1998a). Similarly, strategic application of nitrogen (N) fertilizer improves the performance of most cropping systems, even N-fixing legumes. For example, application of small amounts of starter N to legumes stimulates root growth leading to better nodulation and increased N contribution to a succeeding cereal crop (Giller 2001; Sanginga *et al.* 2001b). More accurate timing and placement of top-dressed N during peak demand of maize greatly improves crop yield and agronomic efficiency (Woomer *et al.* 2004, 2005).

The advantage of integrating management approaches

Based upon research findings across numerous countries and diverse AEZs of sub-Saharan Africa (SSA), a consensus has emerged that the highest and most sustainable gains in crop productivity per unit nutrient are achieved from mixtures of fertilizer and organic inputs (FAO 1989a, b; Pieri 1989; Giller *et al.* 1998b; Vanlauwe *et al.* 2001). The ISFM paradigm results from lengthy investigation into the management of crop nutrition (Table 1.1).

ISFM was derived from Sanchez's earlier Second Paradigm that relies '*more on biological processes by adapting germplasm to adverse soil conditions, enhancing soil biological activity and optimizing nutrient cycling to minimize external inputs and maximize the efficiency of their use*'. Thus, Sanchez recognized the need to combine essential organic inputs with fertilizers and farmer-available organic resources are viewed as a major entry point (Sanchez 1994). Indeed, combining mineral and organic inputs

Table 1.2. Strategic goals and selected ISFM indicators for farmers and evaluators

Land managers' objective	Indicators for land managers	Indicators for policymakers
Maximize profitability of fertilizer and organic inputs	Net increase in farm revenue	Increase in net benefits and product demands
Maximize productivity per unit fertilizer applied	Increase in yield	Change in yield per unit fertilizer
Enhance the soil fertility status	Changes in soil color, feel and water retention	Overall increases in diagnostic soil fertility indicators
Maximize cycling of nutrients	Less fertilizer needed to obtain same yields change in surface soil	Nutrient cycling efficiency and reduces soil nutrient depletion
Maximize water use efficiency	Delayed wilting; less run-off	Increase in water use efficiency and improvement in water quality
Minimize soil loss by erosion	Reduction in soil erosion	Reduction in sediment loads within water catchment
Maintain soil biological diversity	Changes in key species, particularly weeds beneficial soil fauna	Increases in biodiversity indices

result in greater benefits than either input alone through positive interactions between soil biological, chemical and physical properties. However, adoption of the Second Paradigm by farmers was limited by the excessive requirement for land and labor to produce and process organic resources. Farmers proved reluctant to commit land solely to organic resource production at the expense of crops and income.

The Integrated Soil Fertility Management (ISFM) paradigm offers a successive approach by recognizing fertilizer as a key entry point for improving productivity of cropping systems. It asserts that substantial and extremely useful organic resources may be derived as by-products of food crops and livestock enterprise. ISFM also recognizes the importance of an enabling environment that permits farmer investment in soil fertility management, and the critical importance of farm input suppliers and fair produce markets, favorable policies, and properly functioning institutions, particularly agricultural extension.

Strategic objectives and measurable indicators of ISFM

The overall goal of ISFM is to maximize the interactions that result from the potent combination of fertilizers, organic inputs, improved germplasm, and farmer knowledge. The ultimate outcome is improved productivity through wiser farm investments and field practices. Several strategic objectives from land management may be employed to achieve that goal. (Table 1.2). Efficient farming must maximize profitability of soil additions and the productivity per unit inputs applied in a manner that enhances the soil fertility through improved nutrient availability and recycling. Maximizing water use efficiency and minimizing soil loss by erosion are important parallel conditions toward this end. ISFM also offers environmental services through fostering soil biological diversity and sequestering additional carbon within the soil. Several indicators of successful ISFM are available to both land managers and agricultural policymakers (Table 1.2). Farmers can apply simple criteria to their incomes, crops and land to assess the benefits from adopting ISFM practices while the outcome of broader and more complex evaluation may redirect future actions toward rural development and drive needed policy reform.

Large differences exist between reliance upon mineral fertilizer use as a standalone soil fertility management practice compared to ISFM in terms of their respective approaches, scalability and sustainability within smallholder farming systems (Table 1.3). Fertilizer-based technologies are largely product-led in that fertilizers must be manufactured and marketed as packaged products. On the other hand, ISFM is knowledge-driven and requires access to not only fertilizers but also to information that builds a set of flexible principles and permits better decisions concerning soil management. Either approach to soil fertility management may be regarded as technically feasible, with fertilizers requiring larger investment in purchased farm

Table 1.3. Factors affecting the adoption and dissemination of mineral fertilizers and ISFM as complimentary product-led and knowledge-driven technologies.

	Fertilizer-based Green Revolution	Integrated Soil Fertility Management
Approach	Product-led as lost soil nutrients are replaced through the purchase and application of mineral fertilizers.	Knowledge-driven as limited farm resources are strategically complimented by purchased farm inputs.
Feasibility *Does the technology work?*	Applying the right type of fertilizer at the required rate results in improved crop yield and increased farm profits but investment in fertilizer increases farmers' risk during less favorable growing seasons.	Combining mineral fertilizers with organic resources and improved germplasm and integrating them into more efficient farming operations improves fertilizer and water use efficiency, crop yield and profits.
Accessibility *Can the technology reach its intended beneficiaries?*	Mineral fertilizers are industrial products that must be manufactured, packaged, transported and marketed to farmers who are willing and able to purchase and apply them. Fertilizers may be packaged in ways making them more attractive to farmers.	ISFM requires access to information that builds a set of flexible principles empowering farmers to make better decisions concerning allocation of limited available resources and permitting higher yields from modest investment in farm inputs.
Scalability *Can the technology be adjusted over a wide range of conditions?*	Some fertilizers are broadly applicable to different soils and crops while others are intended for specific commercial enterprises. Product information and marketing campaigns increase awareness of fertilizers.	ISFM techniques can readily spread among farmers engaged in similar enterprises, particularly when backstopped by demonstrations, farmer field days and agricultural officers.
Sustainability *Does the technology continue to operate without external support?*	Demand for fertilizers continues when they are efficiently distributed, fairly priced and profitably used. The ability and willingness to purchase additional fertilizers depends upon fair markets for crop surpluses. Fertilizer sales support local business enterprise.	ISFM increases demand for fertilizers and improved seed. Robust practices optimize yield and profits during good growing seasons while reducing risks of drought, pests and disease under less favorable circumstances. ISFM practices enhance soil and environmental quality.

inputs and ISFM making better use of available farm resources and labor, but when these two technologies are used in conjunction, farmers are able to deploy fertilizers and organic resources more effectively. In this way, ISFM may be regarded as providing knowledge and field practices that are crucial to the dissemination of mineral fertilizers to Africa's smallhold farmers.

Key considerations in devising ISFM strategies

Fertilizer advice must not only provide suggested types and rates but also offer guidelines on how to make adjustments in conjunction with the use of commonly available organic resources. For example, manure piles may be protected against nutrient loss resulting in lower amounts of mineral fertilizers required to supplement them. ISFM approaches may follow two parallel paths, one for strictly commercial production that optimizes returns per unit area and another intended for resource poor farmers that makes best use of limited affordable fertilizer. Different resource endowment categories exist within a given farming community and the capacity of each category to invest in mineral fertilizers differs. Similarly, households have different degrees of labor availability.

Farmers producing cereals for markets should be offered one set of recommendations, and those who are seeking food security for the least cost could be offered another set whereby less fertilizer is used more efficiently. Different ISFM advice can be forwarded for characteristic soil fertility niches within farms and for major topographies. Spatial heterogeneity within and across farms results from topography, nutrient and soil gradients and specialized niches and these differences necessarily influence nutrient management. In many cases heterogeneity is intensified from past management when more resources are devoted to nearer or more productive fields.

Separate practices are required for severely degraded and nutrient depleted lands that allow farmers to rehabilitate their least productive fields in a resource and time efficient manner.

Localized fertilizer recommendations are best developed, adjusted and validated through close collaboration between researchers, extension agents, farmer associations and their members. Participatory research methods guarantee farmers' role in the formulation of recommendations, farmers' adaptive and adoptive response to those recommendations and the impacts resulting from them (Defoer 2002). This approach is markedly different from top-down, prescriptive approaches to fertilizer use because it encourages farmers to adjust recommended management practices to their farming conditions and household priority setting (Morris *et al.* 2007). The level of participation can vary depending on the complexity of the knowledge underlying a specific intervention.

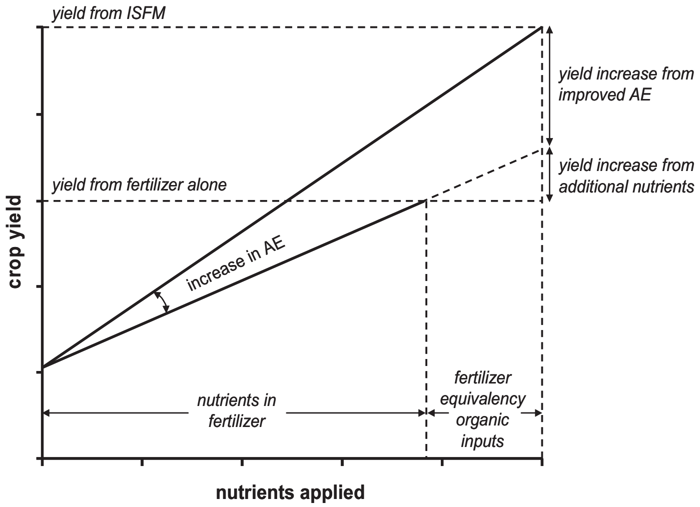


Figure 1.2. Conceptual diagram representing the yield increase from improved agronomic efficiency (AE) of fertilizer and organic resource addition (after Vanlauwe et al. 2001).

The Importance of Agronomic Efficiency

Agronomic efficiency (AE) is a ratio describing the increase in crop yield per unit of applied nutrients. A central feature of ISFM is that it increases the benefits from applying mineral fertilizers in two ways. Applying organic resources in conjunction with mineral fertilizers increases AE and, in many cases contributes additional nutrients (Figure 1.2). AE is also improved through better nutrient retention and improved nutrient release patterns, which is related to improved soil physical and biological properties. Additional nutrients result from the mineralization of plant nutrients during decomposition of organic additions to soil. For purposes of simplification, Figure 1.2 depicts a linear crop response to mineral nutrients, rather than the initial sigmoidal lag at lower levels and attenuation at higher levels, as occurs under field conditions. The linear model is however, valid under moderate rates of fertilizer addition.

Nutrient recoveries of applied fertilizer by crops under farmers' practices are distressingly low. Only about 10-15% of the P and 10-20% of the N and K applied through fertilizer is assimilated by crops. This ineffective use of fertilizer in effect discourages investment in fertilizer by poor African farmers (Africa Fertilizer Summit 2006). Low assimilation efficiencies are commonly a result of several factors. Crops require nutrients in different quantities and proportions. According to Liebig's Law of the Minimum (see Russell 1973), deficiency in one nutrient results in reduced plant growth and less ability to make use of all other nutrients. Most fertilizers only address the primary nutrient requirements of crops (N, P and K). In this way, soil reserves of non-limiting nutrients decline with intensifying cultivation, limiting the use efficiency of these fertilizers that do not contain them (Giller *et al.* 1998a, Vanlauwe *et al.* 2000a,b). However, applying Liebscher's Law of the Optimum, evidence suggests that the lack of one nutrient influences the efficiency of uptake of another one at even non-limiting levels (see De Wit 1992). In this way, stressed crops are limited in their ability to make efficient use of applied nutrients. Drought stress leads to impaired root development. Soil characteristics such as soil crusting, impermeable soil layers, extreme pH levels and Al toxicity negatively affect plant root development and nutrient uptake. Plants suffering pest and disease stresses will not make full use of applied inputs. Finally, ineffective management of inputs leads to nutrient losses and inefficient utilization by crops. Fertilizer application needs to be placed and timed at appropriate rates in accordance with crop nutrient requirements, and tailored to environmental conditions (Adesina 1996). Effective weed management is essential to prevent competition for nutrients and allows efficient uptake by crops.

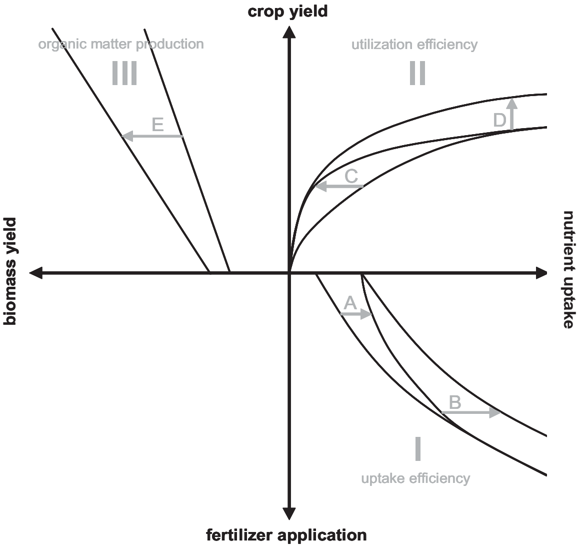


Figure 1.3. Conceptual diagram representing relationships between fertilizer application, nutrient uptake, crop yield and biomass production (from Van Keulen, 1982).

Mechanisms affecting agronomic efficiency. Crop yield and AE are affected by several factors including nutrient uptake and utilization efficiencies and by the levels of soil organic matter resulting from biomass production and recycling (Figure 1.3). Uptake efficiency (Quadrant I) defines the efficiency by which a nutrient is assimilated into the crop (the quantity of nutrient assimilated per quantity of nutrient applied). Utilization efficiency (Quadrant II) defines the efficiency by which a crop transforms assimilated nutrients into yield (yield per quantity of nutrient assimilated). Effective biomass production (Quadrant III) depicts the amount of biomass produced for a given yield. All three are essential elements of AE. Arrows in Figure 1.3 represent increases in efficiency and could be obtained by breeding for more extensive root development and mycorrhizal inoculation or appropriate fertilizer timing and placement (A), removal of other nutrient constraints, water harvesting, soil acidity correction, pest and disease control (B), crop breeding for lower crop nutrient requirements (C & D), and better use of crop residues and crop-livestock integration (E).

Each of these efficiencies can be improved by specific practices or technologies. For example, uptake efficiency can be increased by correctly timing and placing fertilizer (e.g. N top-dressing), utilization efficiency can be increased by using resilient germplasm with lower nutrient requirements and effective organic matter production can be improved by incorporating promiscuous, high biomass-yielding legumes into the cropping system. Furthermore, reducing aluminum toxicity and soil acidity by lime application will increase root formation and function, resulting in enhanced nutrient uptake and internal use. Correcting specific micronutrient deficiencies will allow better utilization of N, P and K applied to the crop with maximal efficiency obtained when all nutrients are supplied at the crop's optimal internal ratios (Bouis *et al.* 1999).

Improvement in agronomic efficiency. Generally, agronomic efficiency can be determined directly as the yield increase obtained from the quantity of nutrients applied, and compared for different technologies and practices. Agronomists can then conduct specific measurements to understand the underlying causes of improved agronomic efficiency. Where different nutrient sources are supplied through inherent soil fertility, release from mineral fertilizers or mineralized

Table 1.4. Response to mineral fertilizers in west Kenya under different input and management regimes (after Woomer 2007).

Management	fertilizer input kg nutrient/ha	maize yield kg ha^{-1}	net return $/ha	benefit: cost ratio	AE kg kg^{-1}
Maize-bean intercrop	none	1483	225	2.3	na
w/ MoA recommendation	59 N & 13 P	2811	403	2.4	18
w/ P replenishment	38 N & 33 P	2600	418	2.6	16
w/ 2 t rock P fortified compost	29 N & 6 P	2206	354	2.6	21
Staggered intercrop w/groundnut	25 N & 13 P	2865	584	3.3	36

from organic resources, methods using isotope labelling of one or more nutrient sources can quantify their various contribution to crop nutrition.

Yield improvement can also be expressed in economic returns, rather than in agronomic production, to take investments in labour and other inputs into consideration. Farmers are inclined to conceive agronomic efficiency in economic terms, as the yield increase obtained needs to justify the investment made. A measurement of agronomic efficiency should therefore always go side-by-side with a benefit:cost ratio when comparing fertilizer use and practices to improve their efficiency (Morris *et al.* 2007). For example, soil fertility management of maize-legume intercropping was examined on 120 on-farm trials in west Kenya over three seasons. The different managements are based upon recommendations forwarded by various rural development interests and are compared side-by-side to permit participating farmers and their neighbours to understand their options for managing investments in mineral fertilizer with ISFM. The fertilizer-based recommendation by the Ministry of Agriculture (MoA) is compared to three ISFM practices in Table 1.4. This recommendation is quite costly to farmers ($294 per ha, data not presented) but results in favorable yields (2.8 t per ha) and economic returns ($403 per ha). Three ISFM alternatives were examined relying upon 1) Tanzanian rock phosphate, 2) fortified compost and 3) staggered intercropping that permits more radiation to reach understorey legumes while maintaining the same maize population. Note that the latter two managements improved AE by 17% and 100% respectively. These ISFM alternatives all resulted in greater benefit:cost ratios and, in the case of MBILI much larger returns (+ $179 per ha). ISFM compensates for reduced fertilizer rates with higher agronomic efficiency, resulting in greater yields and larger profits.

Another comparison of AE in response to ISFM is illustrated through different striga management options receiving the same level of fertilizers. Striga is a parasitic weed native to African grasslands that has now colonized over 22 million ha of cereal cropland and severely threatens food security in maize-based farming systems (AATF 2006; Woomer *et al.* 2008). Severely parasitized maize is unable to respond to the addition of mineral fertilizers (Table 1.5).

Farmers' efforts to manage striga require ISFM practices involving tolerant germplasm, mineral fertilizers, strategic nitrogen addition and legume suppression of the striga seed bank. Once these practices are applied, the agronomic effectiveness of mineral fertilizers applied to striga-infested soils improves between 7- and 13-fold (Table 1.5). Furthermore, advantage over striga can be obtained through the addition of organic materials and fertilizer nitrogen because host cereals are able to assimilate a wider range of nitrogen sources than is the parasite. For example, maize can readily assimilate urea that is deleterious to striga, a broadleaved plant. In this way, ISFM and striga management are closely related and other nutrient deficiencies often become expressed once the plant parasite is brought under control.

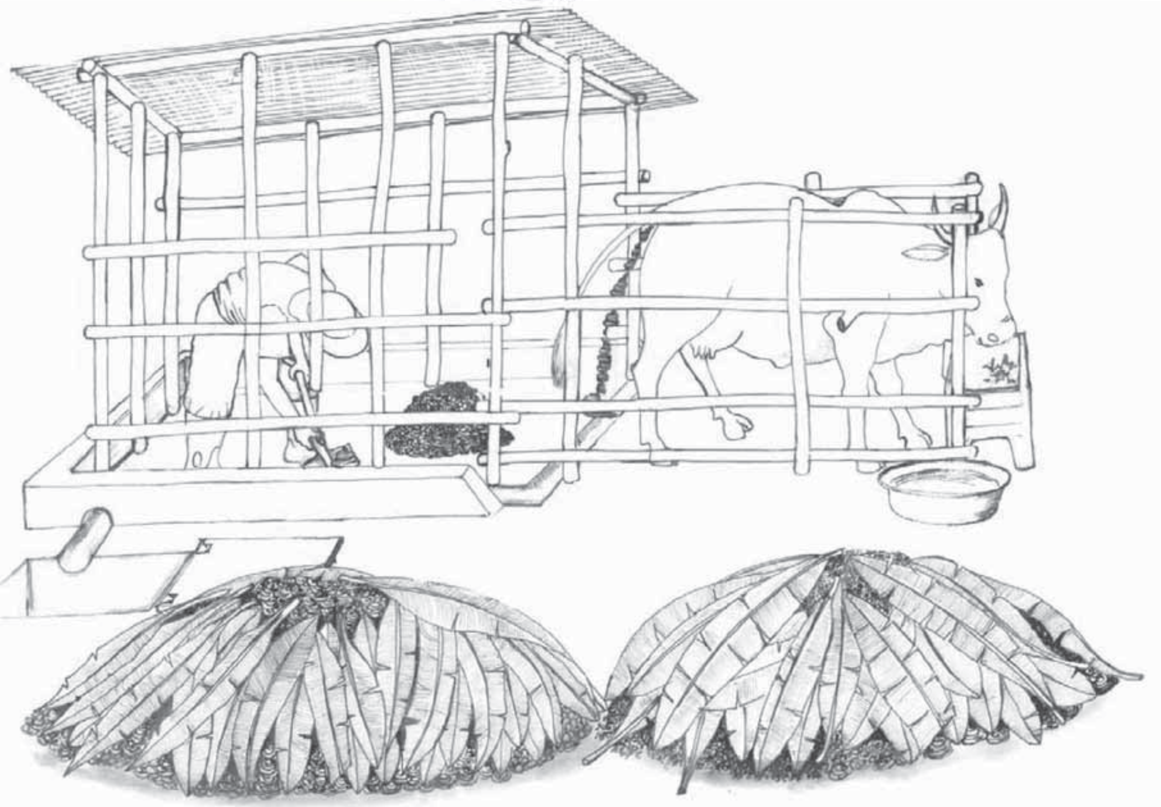
In conclusion, ISFM aims at effective input use by combining a number of nutrient sources and process regulators. ISFM practices involve 1) judicious use of mineral fertilizer and agro-minerals in terms of their form, placement and timing of application, 2) management of crop

Table 1.5. Maize yield, economic return and fertilizer use efficiency in 24 striga infested farms of west Kenya[1] (after Woomer *et al.* 2008).

Management	fertilizer input kg nutrient/ha	maize yield kg ha^{-1}	net return $/ha	benefit: cost ratio	AE^2 kg kg^{-1}
Recommended hybrid H513	24 N & 5 P	1579	228	2.0	3
Push-pull with desmodium	24 N & 5 P	2103	128	1.5	21
Tolerant OPV KSTP 94	24 N & 5 P	2323	348	2.6	28
Herbicide resistant hybrid	24 N & 5 P	2601	371	2.6	38

[1] average over four consecutive seasons in field with <100,000,000 Striga seeds ha^{-1}. [2] maize yield without mineral fertilizer = 1483 kg ha^{-1}

residues and other locally-available organic resources that improve agronomic efficiency, 3) use of locally adapted germplasm that is resistant to local stresses conditions, both biotic and abiotic and 4) other field practices determined by local agricultural conditions, particularly pest and disease management, soil erosion control, moisture conservation and the enhancement of beneficial soil biota. These considerations lead to a suite of field practices based upon past experience, current information and changing farming conditions that result in better soil fertility management. Along these lines, this book seeks to establish a suite of principles and provide solid examples of successful strategies employed by land managers that will advance ISFM as an essential component of rural development in Africa.



Chapter 2. Fertilizer management within ISFM

Nutrient inputs to soils cultivated by small-scale farmers are essential for improved crop production in Africa (African Fertilizer Summit 2006). A wide variety of soils are found in Africa from young alluvial and volcanic soils to ancient Ferrasols (FAO 1977). Some soils are inherently poor or degrading and have a low potential to supply and retain applied nutrients. Nitrogen (N), potassium (K), magnesium (Mg) and calcium (Ca) are easily leached and lost under climates with excessive rainfall. Many soils have a high capacity for phosphorus (P) immobilization, making applied P less available to plants. Furthermore, large regions in Africa are also characterized by strong soil acidity coupled with toxic aluminum (Al).

The use of fertilizer is indispensable to alleviate nutrient constraints, and stands central in ISFM practices for improved crop production. Throughout Africa, however, sufficient mineral fertilizers are not available at the right times during the year. Fertilizer shortage is mainly attributable to high transaction costs and inefficiencies throughout the production – consumption chain (Quiňones *et al.* 1997). Moreover, the little fertilizer available is often not the correct type required for various crops, and farmers are unfamiliar with its correct usage. Fertilizer adulteration is not uncommon in several African countries, and discourages fertilizer investment by farmers.

Africa occupies about 29.8 million square kilometers. Of this area, 31% is desert, 38% is semi-arid dry grassland and woodland, 19% is potentially arable, 10% is humid forest and marsh (Woomer and Muchena 1996). Of the potentially arable lands in sub-Saharan Africa, 165 million ha is cultivated. Approximately 1.38 million tons of fertilizer per year are applied to cultivated lands during 2002 resulting in an average fertilizer consumption of 8.3 kg ha^{-1} (Table 2.1). This consumption represents only 2% of worldwide demand (64.5 million MT) and is by far the lowest rate of fertilizer use in the world (Morris *et al.* 2007). The sub-region produces only 13% of its fertilizers, with the remainder being imported.

The best data for fertilizer production, commerce and use in Africa is compiled annually by the United Nations Food and Agriculture Organization (FAO). For many years, these data were presented in a special Yearbook of Agriculture: Fertilizers. Presently, these data are available over the internet at the FAO website within its FAO-STAT pages (see www.fao.org). While these data are compiled by continent (Table 2.1), sub-regions, and countries and may be used to make generalized comparisons, it is difficult to synthesize them within a comprehensive developmental context in terms of fertilizer use by the small-scale farming sector.

Fertilizer consumption in 38 nations of sub-Saharan Africa is presented in Figure 2.1. This consumption ranges from 0.3 kg ha^{-1} in the Central African Republic to 42.5 kg ha^{-1} in Zimbabwe prior to its questionable land reform. The country data presented in Figure 2.1 are grey-scaled within four African sub-regions (Central, East & Horn, Southern and West Africa). Fertilizer consumption of less than 5 kg ha^{-1} occurs in 55% of these countries. Only five of these nations

Table 2.1. Fertilizer production, consumption, imports and exports in sub-Saharan Africa during 2002 (from FAO-STAT, 2004)[1].

action	fertilizers containing			
	nitrogen	phosphorus	potassium	total fertilizers
	MT			
produce	110300	67050	0	177350
import	709315	410740	288411	1408466
consume	738943	409286	235369	1383598
export	43182	17825	35256	96263

[1] not including South Africa.

are landlocked, suggesting that factors other than inland transportation are affecting their paucity of fertilizer use (Morris *et al.* 2007). Eight of these nations are engaged in, or have recently emerged from conflict, indicating that political stability is an important condition to fertilizer use. The country with the greatest fertilizer consumption in 2004 has undergone economic collapse and is unlikely to retain its position some years later.

Only five nations consume greater than 25 kg of fertilizer per ha. Four of those countries are in Southern Africa and three of these operate under the influence of South Africa's economy. The spike in fertilizer consumption occurring between 15 (Congo) and 25 kg (Kenya) per ha may be superficial. Several countries, such as Kenya and Uganda, experience strong bimodal rainfall that permits cropping twice a year. Humid Central and West Africa have year-round growing conditions. This suggests that the amounts applied per cropping cycle are much less than when consumption is expressed on an annual basis. From these national fertilizer consumption data we can conclude that raising fertilizer use to even the most conservative targets (e.g. 50 kg ha^{-1}) is a daunting challenge because no nation has matched that target and more than 50% of them currently consume less than 10% of that goal.

Fertilizer consumption patterns within nations are often sketchy and inconsistent. Fertilizer recommendations were often formulated decades ago, and expressed as national rather than finer agro-ecological levels. These recommendations disregard variations in crop demand and soil properties, and farmers' access to inputs and commodity markets. Even within more localized recommendation domains, households operate at different stages of economic development. IFDC (2002) has developed a framework describing stages of fertilizer use and applied them to individual African countries. Stage I describes subsistence agriculture where improved crop varieties and mineral fertilizer are unavailable. Stage II depicts emergent agriculture where improved varieties and mineral fertilizers are available for market crops, especially export commodities. At Stage III, mineral fertilizers and improved varieties become available to food producers, resulting in local farm input supply networks. Stage IV describes economic maturity where farming is viewed as a business and the private sector is fully involved in farm input manufacture and supply, and commodity marketing. Because a paucity of fertilizers are manufactured within most countries, consumption matches imports, and these may be reported

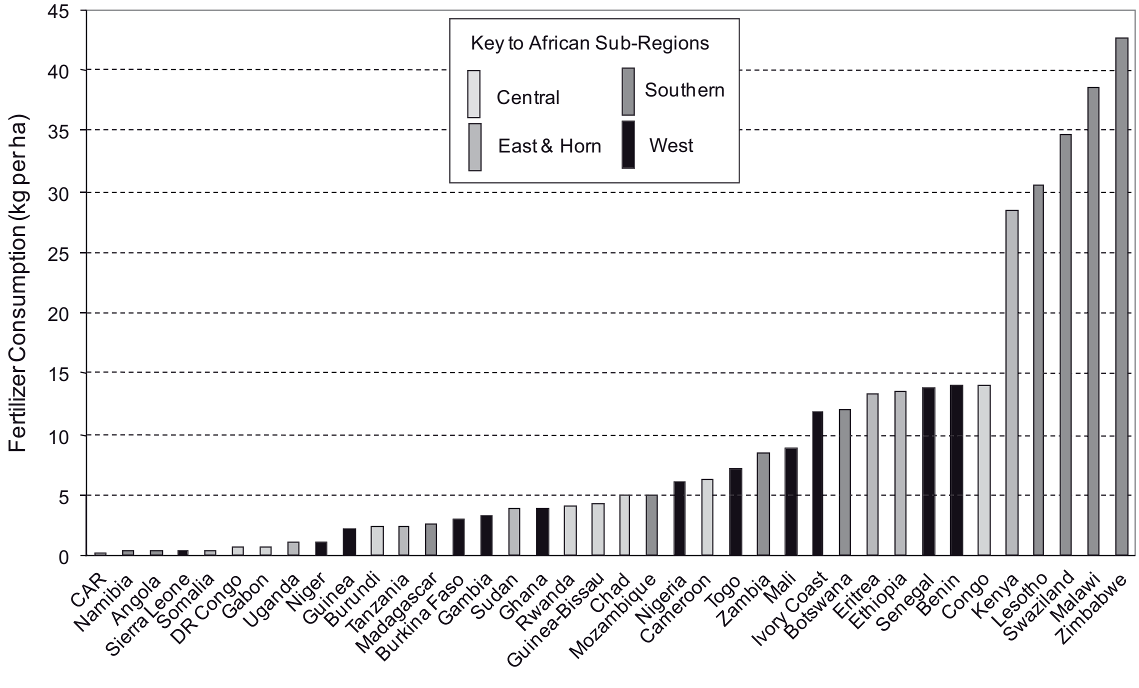


Figure 2.1. Fertilizer consumption in 38 nations of sub-Saharan Africa (FAO-STAT 2004)

among other economic statistics. The disheartening reality is that most fertilizers are being applied to cash crops on larger farms, and even the low consumption in Figure 2.1 is likely an over-estimate of the soil fertility management by small-scale farmers.

Some more localized data on small-scale farmers and their fertilizer use is available from the scientific and developmental literature. Mwaura and Woomer (1999) surveyed 139 farm input retailers in 74 market centers in Kenya to determine the role of soil fertility products within their operations. Small-scale farmers in Kenya's best agricultural lands have access to a variety of fertilizers that are being repackaged into amounts they can afford. Market liberalization has resulted in a growth of fertilizer commerce but local retailers continue to face difficulties, particularly the lack of credit. The frequency of fertilizer product sales is presented in Table 2.2. Although 17 different fertilizers are marketed in Kenya, only three have widespread distribution, DAP, CAN and urea. These three fertilizers are nitrogen-bearing, but DAP also contains phosphorus. These fertilizers are concentrated, meaning nutrients occupy a high proportion of their total composition, suggesting that there is advantage in their transportation (Quiňones *et al.* 1997). Indeed, fertilizer prices are too often high compared to crop commodity prices and the costs per unit nutrient can vary greatly. For example nitrogen from CAN and urea then costed \$1.73 and \$1.12 per kg, respectively (data not presented). Note that Minjingu Rock Phosphate from neighboring Tanzania was not widely available and appears overpriced considering it was sold for only \$50 per ton by its producers in nearby Arusha. Current fertilizer prices from a major supplier in Kenya during May 2009 are also presented in Table 2.2 and serve as an indication of price increases over the past decade. Similar studies are required elsewhere because knowledge of fertilizer availability must be factored into recommendations. Consideration must be given to whether or not fertilizer targets and recommendations should drive the choice of fertilizers offered by stockists, or whether they should be nested within what is currently available and in demand.

Another approach to understanding fertilizer use by small-scale farmers is to survey them directly. Soule and Shepherd (1998) concluded that fertilizer use in West Kenya was limited to the households with the most favorable resource endowments. Crowley and Carter (2000) reported a somewhat wider use of fertilizers. Their results showed that more than 90% of farmers in two villages used chemical fertilizers. This is contrary to a general belief that they are not widely applied to food crops by smallholders in African agriculture. However, up to 81% of the fields received less than half of the recommended 120 kg N ha^{-1} because of high costs due to removal of subsidies and inefficient marketing systems. Use of organic inputs such as animal manure (29% of farmers), green manure (22% of farmers), and household refuse (19% of fields) were less popular among farmers. However there is evidence of combined use of inorganic

Table 2.2. Fertilizer availability from retail farm input suppliers in Kenya (after Mwaura and Woomer 1999)[1] with updated prices.

Formulation	Frequency	Price (in 2009)	
	(%)	(\$ per 50 kg bag)	(\$ per kg nutrient)
Diammonium Phosphate (DAP)	94	35	1.81
Calcium Ammonium Nitrate (CAN)	81	27	2.03
Urea	43	29	1.25
NPK Triple 17	28	37	1.90
Triple Super Phosphate (TSP)	11	57	5.64
Minjingu Rock Phosphate	2	26	4.04
Murate of Potash	4	50	3.03

[1] Based upon surveys of 139 retailers operating in 74 market centers.

fertilizers and organic manure on many (24%) of the fields.

A more recent investigation on farming practice in west Kenya was conducted by F.M. Mwaura (personal communication) in preparation for the establishment of smallholder marketing services (SACRED Africa 2004). Unlike these earlier studies, the lead researcher personally conducted each interview and was able to consult with households in local languages. These findings are presented in Table 2.3. Like these earlier studies, Mwaura observed large differences between resource endowment categories in terms of soil fertility management and food security, but unlike earlier studies the poorer farmers appear to make use of fertilizers and organic resources as well. Admittedly, purchase of only 14 kg of fertilizer or use of manure from only one cow is unlikely to greatly improve crop nutrition and yield, but clearly, these farmers have experience with both fertilizer and organic resource management and are likely to become receptive clients of ISFM. Many of these farmers were influenced by the intensive fertilizer marketing efforts of Sustainable Community Oriented Development Programme (SCODP) (Seward and Okello 1999; Conway and Toenniessen 2003). These findings contradict the assertion of Tripp (2006) that no evidence supports the adoption of low external input technologies by Kenya's poorest farmers and also suggest that improved soil management practices are being steadily adopted within west Kenya, albeit at a slow rate.

Curiously, relatively poor use is made of top-dressed fertilizers and the better timing and placement of them appears to be a promising entry point for improved targeting of fertilizers. It is important to notice that a majority of the poorest farmers sell some maize even though few consider themselves food secure. This situation reflects a dilemma in encouraging investment in farm inputs among peasants who must sell their needed food in order to purchase medicines and pay school fees. It is promising to note that a majority of households belong to local farmer organizations and, indeed, these groups have an important role to play in initiatives to encourage investment by improving market access and fairness. Again, more of these surveys are required elsewhere in Africa to provide a solid baseline upon which to establish targets and frame recommendations, and the tools and skills necessary for meaningful household characterization are important to the expansion of ISFM. Currently, NGOs working with these farmers recommend 21 to 35 kg N applied as pre-plant and top-dressed applications in the most fertile soils, and the use of NPK blends in the least fertile soils (mostly sands and highly weathered clays).

Table 2.3. Soil fertility management by farm households in west Kenya belonging to three different resource endowment categories[1].

Parameter	Household Resource Endowment		
	Poor	Moderate	High
Proportion of sample (%)	28	33	39
Farm size (ha)	0.4	0.9	3.8
Average maize yield (kg ha-1)	1246	1616	1550
Fertilizer inputs to maize(kg)	14	71	229
Apply pre-plant fertilizer (%)	45	63	90
Apply top-dress fertilizer (%)	7	27	49
Number of cattle	0.5	1.9	5.5
Apply manure (%)	32	16	13
Plant commercial maize hybrids (%)	10	21	32
Per capita maize supply(kg)	28	68	99
Consider themselves food secure (%)	14	34	53
Sell some maize (%)	64	72	85
Belong to farmer organizations (%)	49	63	68

[1] based upon 247 maize-producing households surveyed by F.M. Mwaura during 2004-2005. Endowment categories are based upon Shepherd and Soule (1998).

Several factors constrain our current understanding of fertilizer adoption and use by small-scale farmers (Fujisaka 1994). Limited information is available on links between fertilizer use and soil management, especially tillage systems, and how fertilizers may be better incorporated. Women's poorer access to farm inputs, capital and credit requires greater understanding before gender can be factored into ISFM recommendations (Gladwin *et al.* 1997). There is lack of consistency in fertilizer use data for different regions and countries and at finer scales, particularly 1:50,000 where individual farms may be distinguished. Role and effectiveness of extension services varies between countries and farmers' response to weak extension is not well characterized. Off-farm income allows investment in fertilizers, but household willingness to do so is not well understood. Social and cultural factors have a strong influence on farm practice, and these must be better described and interpreted within the context of targeting and recommending fertilizers.

In most African countries, fertilizer recommendations have been effective in modifying cultural practices of major export and food crops on large commercial farms, but have had little impact on smallholder production systems beyond those in the higher resource endowment category. The export and cash crops that stimulate fertilizer adoption include coffee, tea, sugar cane, cotton and, to a lesser extent groundnuts, rice and other cereals. The reasons for this difference are complicated owing to the range of cash crops and their market setting but some trends are evident. Special fertilizer formulations are available for export crops and farmers recognize that their use improves yields, quality and profits. Cash crop producers are also better positioned to receive short-term credit for the purchase of farm inputs.

As farmers move from subsistence to market agriculture, their farm enterprises diversify and opportunities for the adoption of fertilizers are presented. It is important that farmers recognize that mineral fertilizers are not intended for cash crops only, but field crops benefit as well. This is particularly the case where strong market potential exists for cereals, pulses and root crops. Export crops are often produced within rigid out-grower schemes where farmers receive predetermined inputs (seed, fertilizers and pesticides) on credit from the commodity buyer, and then have repayment deducted from their harvest revenues. This is the case for externally supplied outgrower activities in sugar cane, tea and cotton production in East Africa. Perhaps it is stretching the point to describe these farmers as fertilizer adopters. In some cases, out-growers are supervised by credit providers to ensure that fertilizers are applied to their intended commodity rather than redirected to other fields or resold. These farmers apply fertilizers without developing important knowledge about their different formulations and management and it is important that narrow views toward fertilizer use be broadened as they venture into new commodities and markets.

Farmers are aware of the maximum yields they can obtain in different fields, which they recognize as good (well-managed), medium (reasonably-managed) and poor (degraded) fields. This local knowledge can be used to set the maximum amounts of fertilizer to be applied to each field type, according to the expected potential yield. Fields that farmers know are poorly-responsive need to be rehabilitated by application of organic manures before fertilizer should be recommended. In the least responsive fields, applications of a wider range of nutrients than simply N, P, and K that include Ca, Mg, S and micronutrients may prove necessary to provide more balanced nutrient supply.

Use of the correct type of fertilizer is of paramount importance for their efficient utilization. Nutrients supplied through mineral fertilizers must match crop requirements. Knowledge of soil characteristics and processes regulating nutrient availability and supply to crops is essential to raise production per unit of fertilizer nutrient applied. A multi-locational fertilizer use recommendation project in Kenya revealed large locational differences in crop response to fertilizer application (Table 2.4). In some soils, maize responded only to P application or only to N application, while in others both N and P inputs were essential to increase crop production (Smaling *et al.* 1992).

A recent study revealed large-scale S deficiency in northern Nigeria (Franke *et al.* 2004). As a result, many crops no longer respond to P application, supplied as TSP fertilizer. This could straightforwardly be amended by replacing TSP with SSP, a sulphur-containing P fertilizer. Assuring farmers that fertilizers supply the correct nutrients required by the crop and tailored to local soil conditions is a necessary condition for adoption within nutrient management initiatives and one that must remain prominent within fertilizer extension and rural development agendas.

Table 2.4. Yields and NPK uptake of maize on three Kenyan soils as a function of soil type and fertilizer treatment in the long rainy season of 1990 (Smaling et al. 1992).

Soil	fertilizer nutrients applied	maize yield	N uptake	P uptake
		t ha^{-1}	--------- kg ha^{-1}	--------
Nitisol (P-fixing)	0	2.1	42	5
	50 kg N ha^{-1}	2.3	50	6
	22 kg P ha^{-1}	4.9	79	12
Vertisol (fertile, not P-fixing)	0	4.5	63	24
	50 kg N ha^{-1}	6.3	109	35
	22 kg P ha^{-1}	4.7	70	23
Arenosol (sandy, poor in nutrients)	0	2.5	38	7
	50 kg N ha^{-1}	2.2	45	7
	22 kg P ha^{-1}	2.3	38	11
	50 kg N + 30 kg P ha^{-1}	3.7	66	16

Availability, quality and utilization of mineral fertilizer

Fertilizer manufacturers and distributors commonly lack the essential agronomic information to formulate appropriate nutrient compositions of their product. Crop nutrient requirements depend on the environment and change with time and intensifying crop production. Ineffective linkages with experimental stations and lack of regular farmer surveys hamper this information. Fertilizer quality loss due to poor storage and adulteration occurring during repackaging are other constraints that discourage farmer investments in fertilizer.

A major problem for effective utilization of fertilizers and ISFM practices in Africa has been inability to deliver appropriate recommendations and accompanying inputs in the right form to smallhold farmers. Past fertilizer recommendations have too often been based on single major cash crops such as maize, tea and cotton, failing to take into account spatial variation in smallholders' resource endowment. There is need, therefore, to move away from more generalized fertilizer recommendations and instead base guidelines for fertilizer use on the principles of ISFM, targeting dissemination programs to the specific crop production problems faced by farmers.

Several steps are required before fertilizers of the correct type are sufficiently available to smallhold farmers in Africa and become adopted within the context of ISFM. First, better diagnosis of soil and plant constraints by rural planners must be performed so that the correct types and blends of fertilizers become available. Then the use of these fertilizers must become nested within ISFM advice targeted to farmer's agro-ecological setting, production strategy and socio-economic conditions. To achieve this goal, human and institutional capacities must be directed toward finding solutions to soil constraints that make best use of farmers' limited resources and that balance the benefits of redirecting cash investment and labor.

There is growing evidence that meeting this challenge in SSA will require more attention to soil fertility issues than was the case elsewhere. Farmers' fields are characterized by low inherent fertility and continuous cultivation without inputs (Bationo *et al.* 2006). In many cases, farmers yields for cereals rarely exceed 0.5 t ha^{-1} while a potential of 6-8 t ha^{-1} is attained at on-station trials and by some commercial farmers. As a result, there is a great yield gap between the experimental station yields, potential farmers' yields and actual farmers yield (Figure 2.2). This yield gap can be attributed to several constraints, mainly biological (varieties, weeds, disease and insects, water and nutrient deficiencies) and socio-economic (costs and benefits, access to credit and inputs, attitude, among others).

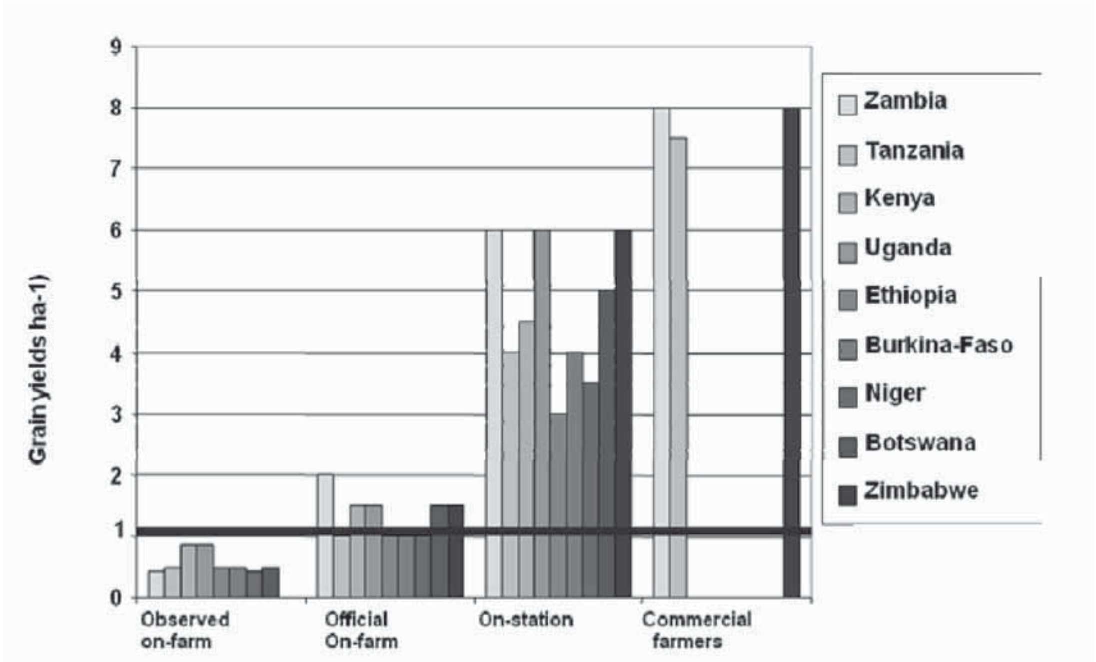


Figure 2.2. Reported maize grain levels in selected countries in sub-Saharan Africa indicating a substantial yield gap between on-farm, station and commercial activities (Bationo *et al.* 2006).

ISFM guidelines for integrated fertilizer use

The craft of ISFM involves making the best use of affordable fertilizers, available organic resources and accessible agro-minerals. Better management of fertilizer calls for increased farmer knowledge through information and training campaigns. Corresponding actions include promotion of fertilizer micro-dosing, water conservation, management of soil organic matter, better integration of legumes into farm enterprises and mobilization of available agro-minerals. Lack of farmer knowledge on production, conservation and effective utilization of organic fertilizer is also a constraint that needs to be addressed through accompanying information.

Guidelines in ISFM practice cover generalized practices for different sorts of fertilizers, and more specialized approaches to specific categories of land and household resource endowment. As advice becomes more localized, greater knowledge of ISFM is required. Ultimately, it is the responsibility of individual farmers as ISFM practitioners to make adjustments to local recommendations based upon their specific conditions. Examples of ISFM guidelines follow.

Optimize micro-dosing and top-dressing of nitrogen fertilizers and conduct campaigns to increase the use and effectiveness of these practices. Applying fertilizers in micro-dose amounts permits more precise and better timed fertilizer placement, particularly in conjunction with water harvesting. Top-dressing cereals with nitrogen-bearing fertilizers is a near universal requirement for highly profitable cereal and green vegetable production that is too seldom practiced by smallholders. Timing micro-dosing and top-dressing to the rains is a skill required by farmers because it improves fertilizer use efficiency and reduces the consequences of drought. Different top-dressed fertilizers require special timing and placement and these are not fully understood within the context of smallholder practice.

Match different water conservation measures to specific dryland and soil conditions. Several technologies exist to improve water availability in drought-constrained areas, including practices that also improve the soil organic matter content. These technologies involve water

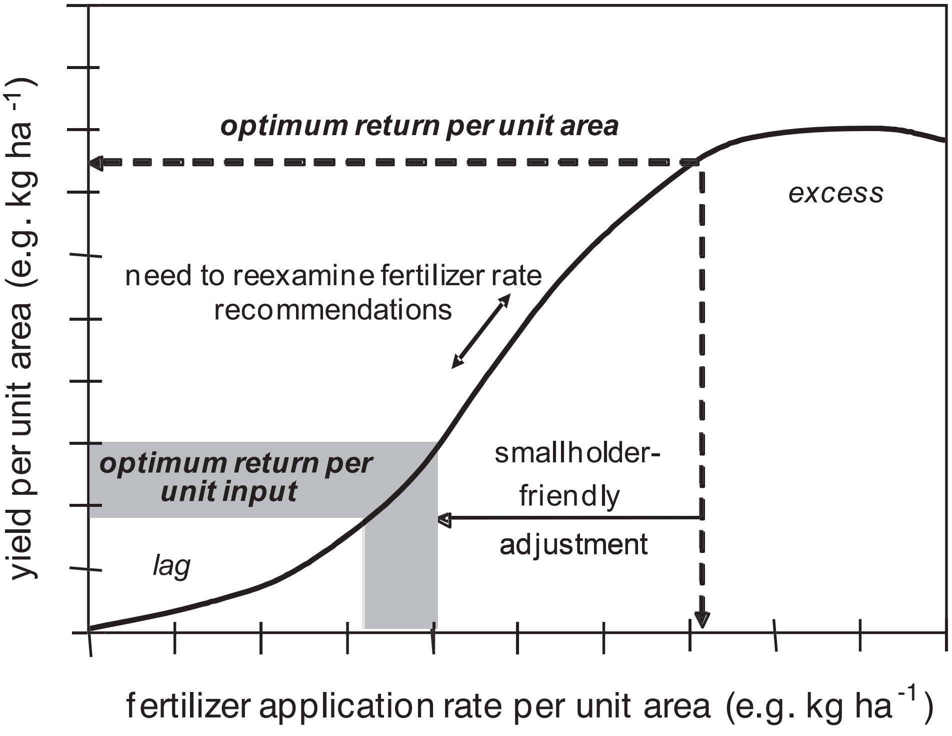


Figure 2.3. Fertilizer recommendations formulated for small-scale farmers should be based not upon maximizing return per unit area, as is customary, but rather optimizing return per unit fertilizer input.

harvesting using *zai* planting pits (Cofie *et al.* 2004), half moon catchments, stone bunds and tied ridging. Water harvesting strongly interacts with nutrient management. Combining water harvesting techniques with micro-dosed fertilizer, agro-minerals and manure application results in substantial increases in crop yield (Bationo 2008). Existing recommendations on water harvesting need to be translated into more targeted decision-support systems, simplified into field practices facilitated through extension services and national programs.

Better manage soil organic matter through ISFM. The basic soil processes and climate influences governing soil organic matter (SOM) turnover are well-understood (Woomer and Swift 1994). The major challenge resides in producing sufficient organic materials within the cropping system to maintain or increase SOM as by-products of profitable cropping. Fertilizer is a key entry point toward organic matter management through greater root biomass production, symbiotic N fixation and soil conservation. Other approaches to SOM management include: 1) Conservation Agriculture practices involving fertilizer application to increase crop residues for mulching, weed suppression and improved water infiltration and storage, 2) crop-livestock integration using forage crops for the benefits of manure production (Elbasha *et al.* 1999) and 3) improved fallows that allocate part of the cropland to organic resource matter production, depending upon the availability of land and labour. Dissemination of techniques that protect the quality of stored organic resources such as manure heaps and composts are also required.

Promote legume-based ISFM practice for striga, pest and disease management. The incorporation of legumes into cropping systems provides additional benefits besides N input, particularly in terms of pest and disease control. An important example is the essential role of legumes in striga management (AATF 2006). Striga is a parasitic weed that has currently colonized over 22 million hectare of cropland causing severe cereal yield reductions. Legumes are generally not suitable hosts but are able to induce suicidal germination, tricking striga seed to

Fertilizer	Accompanying ISFM practice	Rationale for ISFM
DAP	*pre-plant:* apply at least 0.5 t ha^{-1} of manure or compost	Manure and compost are rich in nutrient bases and micronutrients and improve nutrient retention
DAP	*pre-plant:* periodically apply ground limestone	DAP is acid-forming and may require periodic pH adjustment (>5.5)
urea	*pre-plant:* retain some crop residues and incorporate with rock phosphate as a substrate for DAP	Decomposing crop residues solubilize rock P, promote N transformation and provide short-term immobilization preventing N loss
urea	*top-dressing:* apply in conjunction with later weeding	Incorporating urea and weed biomass prevents ammonia volatilization and improves use efficiency
CAN	*pre-plant:* stimulate symbiotic legumes	Apply small amounts of starter N to legumes to stimulate root development, too large applications suppress BNF
CAN	*top-dressing:* apply to cereals in micro-dose placement, avoiding symbiotic legumes	More accurate placement of top-dressing improves N use supply and efficiency during peak N demand
KCL	*pre-plant:* apply manure or dolomite	Maintain proper base nutrient ratios by supplementing K with Ca and Mg

break dormancy and perish. In the medium- to long-term, this results in reduced striga seed banks. Accompanying short-term management practices such as use of herbicide resistant maize, fertilizer management and weeding of striga plants to avoid seed accumulation are equally important in the rehabilitation of striga-infested land (Woomer 2008).

Target returns per unit input not per unit area. Many fertilizer recommendations made to small-scale farmers are regarded as excessive and rightfully so. Fertilizer recommendations are generally based upon sound field trials, but too often, they are formulated by optimizing returns per *unit area* rather than *unit input.* Expressing gains per *unit area* are appropriate to commercial production, but this approach is inappropriate to more limited investments in fertilizer by cash-poor farmers (Figure 2.3). Recommended fertilizer rates based upon the greatest returns per unit input are usually 30% to 50% of those based upon unit area. This implies that if a farmer can afford to fertilize only 1/3 of the farm at the *unit area* recommended rate, then she is usually better off by applying only 1/3 of that rate to the entire farm. At the same time, farmers must be discouraged from broadcasting trace amounts of fertilizer (e.g. 10-20 kg ha^{-1}) as these may be absorbed into the soil with little immediate effect on crops (see "lag" in Figure 2.3). Nonetheless, it is critical that fertilizer recommendations be re-examined within this context and adjusted downward to levels better afforded by small-scale farmers. Different fertilizers may be managed in different ways particularly within the context of ISFM (Table 2.5). Furthermore, fertilizer recommendations are only starting points in fine-tuning a land manager's nutrient management strategy. More localized fertilizer recommendations are best developed, adjusted and validated through close collaboration between researchers, extension agents and farms. In this way, farmers may be empowered to undertake adaptive adjustments to local recommendations that meet the requirements of their individual farms and fields.

Chapter 3. Agro-minerals in ISFM

Many African countries are richly endowed with agro-minerals including phosphate rocks, potassium- and sulphur-containing minerals, lime and dolomite deposits that can either be utilized directly as nutrient sources or serve as raw materials in fertilizer processing. In many cases, agro-minerals can offer a cost-effective alternative to processed mineral fertilizers but in others, agro-minerals are less reactive in soil and nutrient release requires accompanying technologies such as partial acidulation or use in conjunction with organic inputs. Overall, these resources are under-utilized considering their abundance in Africa and their lower cost, but too often they fail to reach needy small-scale farmers because of inefficiencies in the mining, processing and retailing of these materials. Much of the information in this chapter was drawn from van Straaten (2002) and IFDC (2003) and readers requiring additional information on agro-minerals in Africa are referred to these seminal works.

Agro-minerals in Africa

Nearly every country in sub-Saharan Africa is endowed with a variety of agro-mineral deposits (Table 3.1). Phosphate rock and limestone deposits are most common, but other significant deposits of gypsum, pyrite and potash are distributed throughout the sub-regions. African agro-minerals also include a variety of soil conditioners that are of use in higher value agriculture and nursery operations. Agro-minerals tend to contain slightly fewer nutrients than mineral fertilizers (Table 3.2), and to release those minerals over a longer interval but nonetheless their more effective utilization is a critical component of soil fertility maintenance. Clearly, the challenge is less the discovery of agro-minerals for use by African farmers, but rather how to better mobilize existing deposits. Within the context of ISFM, exploitation of agro-minerals spans industrial-scale mining and transformation into mineral fertilizers for international distribution, mid-scale recovery and crushing to reduce national dependence upon fertilizer imports to small-scale mining and use of local deposits. A brief description of the important agro-minerals found in Africa follows.

Rock phosphates. Africa has 4.5 billion tons of well distributed phosphate rock (PR) deposits, representing about 75% of world reserves (Figure 3.1). These deposits constitute a potential P source to address nutrient limitations (Sanchez *et al.* 1997), and could be utilized as an alternative to more expensive fertilizer imports. Presently small-scale farmers make little use of phosphate rock. Mining and processing into fertilizer is costly. Transporting sulphuric acid to mining sites to acidify and enhance solubility of PR is a potential economic alternative, particularly for land-locked countries like Zambia and Uganda, as shown by studies performed by IFDC (2003) and the School of Mines, University of Zambia. Direct use entails higher application rates due to the lower solubility and reduced P content, compared to P fertilizer, and consequently increases transportation costs (Omamo 1998). Dissolution of directly applied PR requires specific soil and moisture conditions, and crop responses are site-specific (Vanlauwe *et al.* 2000b). In the end, cost-effectiveness determines whether farmers will apply PR (Buerkert *et al.* 2001). Some of the more reactive rocks like Tilemsi PR in Mali, Matam PR in Senegal and Minjingu PR in Tanzania have a greater potential for direct use. IFDC recently produced a PR decision support model to calculate crop responses to direct PR application, based on PR type, crop grown, soil and climate properties, and calibrated against extensive agronomic data. Research results also show that a one-time large application of PR has positive residual effects on crop yields during several consecutive cropping seasons, which justifies the use of PR to improve the soil's P status (Mokwunye 1995; Buresh *et al.* 1997).

Table 3.1. The agro-mineral deposits of African nations and their potential for significant economic growth. (based upon van Straaten 2002).

Country[1]	P rock[2]	limestone	potash	S-bearing	Other	potential
Angola	+	+	+	+	glauconite	moderate
Benin	+	+	-	-	peat	small
Botswana	-	+	-	±		small
Burkina Faso	++	+	-	-		large
Burundi	±	+	-	-	peat	small
Cameroon	±	±	-	-		unknown
CAR	±	+	-	-		unknown
Chad	-	+	-	±		small
DR Congo	+	-	-	++	peat	moderate
R of Congo	++	+	++	-		large
Cote d'Ivoire	±	±	-	-		small
Eritrea	-	+	+	-		small
Ethiopia	+	+	+	+	pumice	large
Gabon	±	+	-	-		small
Ghana	-	+	-	±		small
Kenya	±	++	-	+	nitrates	large
Madagascar	++	+	-	+	guano	large
Malawi	+	+	±	±	vermiculite	large
Mali	++	++	±	++		large
Mauritania	+	+	-	++		moderate
Mozambique	+	++	-	+	guano	large
Namibia	±	+	+	-	guano	large
Niger	++	+	-	+		moderate
Nigeria	+	++	-	±		moderate
Rwanda	-	+	-	-	peat	small
Senegal	++	±	-	±	peat	large
Somalia	+	++	-	±	guano	uncertain
South Africa	++	++	-	++	vermiculite	large
Sudan	+	+	-	+		moderate
Tanzania	++	++	-	+	guano	large
Togo	+	++	-	-		moderate
Uganda	+	+	±	+	vermiculite	moderate
Zambia	++	++	-	+	guano	large
Zimbabwe	++	++	-	+	vermiculite	large

[1] Djibouti, Gambia, Guinea, Lesotho, Liberia, Sierra Leone and Swaziland lack significant agro-mineral deposits. Atlantic and Indian Ocean states not considered. [2] ++ indicates proven large, accessible and economically viable reserves, + indicates significant reserves, ± indicates marginal or questionable reserves, - indicates no reserves.

Mobilizing rock phosphates for use by African smallholders is a necessary condition to Africa's agricultural future. It is ironic that rock phosphates mined in Africa are exported to Europe and then re-imported to Africa as pricy, processed fertilizer. The great advantage of

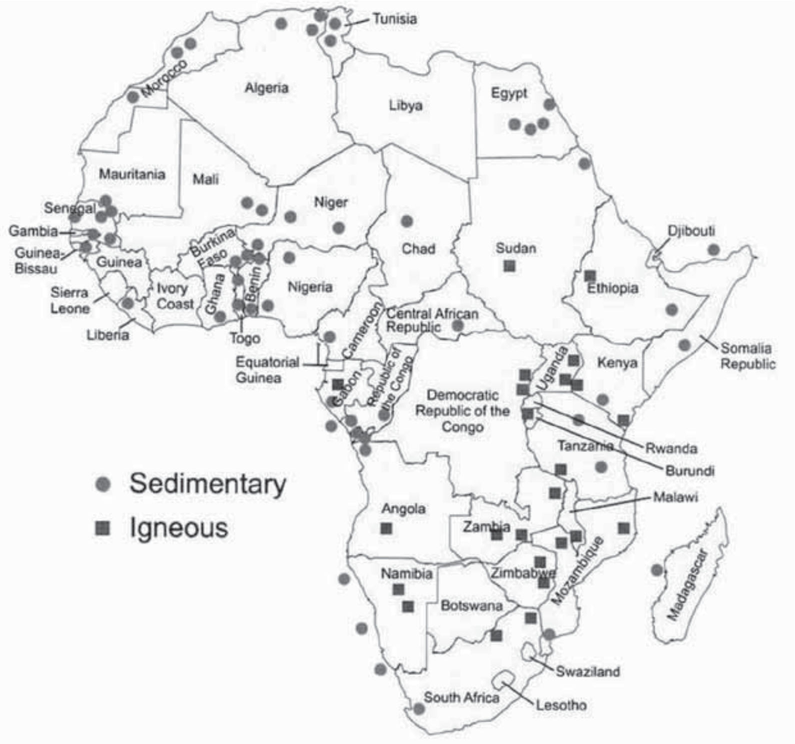


Figure 3.1. Sedimentary and igneous deposits of phosphate rock in Africa (after van Kauwenbergh, 2006)

African rock phosphates are their low price compared to imported P-bearing fertilizers. For example, finely ground, bagged Minjingu PR sells for between \$200 and \$400 ton^{-1}, containing 67% of the P in triple super phosphate (TSP) costing \$1140 ton^{-1} from fertilizer wholesalers.

ISFM involves the combination of PR with organic resources and legumes with root systems that readily solubilize PR. Greater effort must be made to assess the economic benefits from the addition of PR and means found to better process and distribute these products for use by smallhold farmers. Sedimentary and igneous deposits of PR vary greatly in terms of their nutrient concentrations and solubility, but many are able to be used in raw or semi-processed form, particularly when combined with applied organic resources. Two important developments are required before rock phosphates can become widely used by African farmers: 1) the fertilizer industry must increase the solubility of non-reactive PRs through co-granulation or partial acidulation and 2) national programs for mass distribution of PR products must be developed in areas with widespread P deficiency in a manner consistent with proven economic feasibility.

Successes in the use of PR for direct application in SSA are limited and experiences with less reactive PR have discouraged many farmers. However, readily dissolving PRs may be applied to soils after crushing and grinding. Need exists to demonstrate the usefulness of these agro-minerals to farmers. Documentation of existing information, marketing feasibility studies, assessment of socio-economics of the use of agro-minerals as substitutes for more costly imported fertilizers and in building soil capital are important steps towards this goal.

Compelling evidence for the use of rock P in East Africa is provided by Woomer *et al.* (1997). A comparison between Tanzanian Minjingu rock P (MRP) and imported TSP revealed that MRP cost \$50 a ton and was transported for \$0.08 per km ton. Thus, MRP was available in P-deficient West Kenya for \$115 per ton where TSP at the time cost \$480 per ton. MRP was 65% as effective as TSP on an equal P basis and contains 69% as much P on a unit basis, therefore MRP is 45% as effective at only 24% of the cost. The authors then assessed three different possible mechanisms for P replenishment involving market-led, fertilizer relief and ISFM approaches. Few agro-dealers (2%) marketed MRP and clearly better delivery mechanisms are needed. Furthermore, the farmers in the greatest need of P fertilizers tend to be the poorest as well. Fertilizer relief permits needed rock P to stream toward impoverished fields and farmers but this can also interfere with the market development of farm input suppliers. Integrated solutions involving credit to input suppliers and cost sharing with farmers that acquire P through farm

Type and source	nutrient amounts -------- kg ton^{-1} -------	comments
Phosphate rock		
Minjingu, Tanzania	150 P, 11 K, 330 Ca, 20 Mg	Biogenic deposit
Panda, Tanzania	80 P, 30 K, 19 Ca, 8 Mg	Igneous deposit
Busumbu, Uganda	59 P, 64 K, 199 Ca	Soft sedimentary deposit
Dorowa, Zimbabwe	158 P, 222 Fe	Igneous deposit
Taiba, Senegal	103 P	Reserves of 100 million tons
Limestone		
Tengwe, Zimbabwe	160 Ca	Dolomitic limestone
SOTOMA, Togo	207 Ca, 120 Mg	Dolomitic marble mining waste
Guano		
Suswa, Kenya	85 N,47 P, 25 K, 6 Ca, 14 Mg	Bat deposit
Chyulu hills, Kenya	104 N, 45 P, 21 K, 6 Ca, 8 Mg	Bat deposit
Juan de Nova, Madagascar	125 P, 314 Ca	Numerous seabird deposits
Mabura, Zimbabwe	93 N, 64 P	Contains histoplasmosis
Gypsum		
Kibuku, Uganda	232 Ca, 186 S	Reserves of 12 million tons
Pindiro, Tanzania	197 Ca, 158 S	Reserves of 5 million tons
Pyrite		
Iron Duke Mine, Zimbabwe	355 S, 534 Fe	Up to 70,000 tons per year
Nampunwe, Zambia	168 S	Approximately 10 million tons
Potash		
Holle, Republic of Congo	197 K	700 m depth, flooded in 1977
Musley, Ethiopia	174 K	100 to 600 m depth

associations is a solid approach to P replenishment. In return for cost sharing, farmers should be expected to control soil erosion and either retain crop residues or apply animal manure. One approach to P replenishment (45 kg P in 400 kg of MRP per ha) improves maize yield in the first year by 1 ton, resulting in an agronomic efficiency of 23. Nonetheless, making better use of MRP in East Africa presents a challenge to rural development specialists. The Minjingu mine contains 6.6 million tons of P reserves, and has a processing capacity of 100,000 tons per year but over the past several years only 2,000 tons per year were delivered for use in severely P-deficient soils of neighboring Kenya. In 2008, further restrictions on export of MPR were imposed by the Tanzanian Government as a means of stimulating domestic consumption at the expense of sub-regional promotion

Limestone and dolomite. Limestone is the most common agro-mineral in Africa. Agricultural liming materials are composed of calcium and magnesium carbonates that are capable of neutralizing soil acidity, stimulating soil microbial activity and supplying calcium and magnesium to plants. Limestone is rich in calcium and dolomite is also higher in magnesium, with dolomite being slightly more reactive. To be useful, these materials must be finely ground and in some cases hydrated. Quicklime results from heating limestone to 900°C that increases its reactivity by

36%. In general, quality deposits of limestone and dolomite must only be finely ground to be agronomically effective.

Several sources of limestone are available. Sedimentary deposits and fossilized coral are preferable because they are "softer" than crystalline forms such as marble. Nonetheless, quarry dusts from marble mining may also serve as agricultural lime. The most widespread supply of lime is from the cement industry but this source is always low in magnesium as it is detrimental to cement quality. Huge deposits of dolomite are identified but less often exploited. For example, a deposit in Zimbabwe at Tengwe covers an area of 130 km^2 (van Straaten 2002). In some cases, lime is a by-product of other industrial processes such as the beneficiation of rock phosphates.

Under continuous cultivation, both the non-use of fertilizers, as well as the sole use of fertilizer with a so-called 'negative base equivalent' (e.g. CAN and DAP) will cause rapid soil acidification. Acidification increases concentrations of Al in the soil solution, which is toxic to plants. African soils are highly susceptible to this phenomenon due to their inherent low buffering capacity. Lime application can be used to alleviate soil acidity but liming is too often an overlooked component of ISFM practice. Raising soil pH results in greater activities of soil bacteria, which in turn mineralizes other nutrients. This priming effect is significant but usually short-lived. Raising pH also results in conversion of many micronutrients into forms and valence states that are preferred by plants. In this way, effects of liming are confounded by creating a more favorable pH in the soil, selectively promoting beneficial soil organisms and directly supplying calcium and magnesium to plants.

Sulphur, pyrite and gypsum. Three sources of sulphur (S) include elemental sulphur, pyrite (iron sulphide) and gypsum (calcium sulphate). Elemental sulphur is nearly pure S and rapidly reacts with water in soil, lowering the pH. In this way, elemental sulphur may be combined with rock P to increase its solubility. Pyrite contains 22 to 30% S and is most useful on calcareous soils as a source of both sulphur and iron. Gypsum has the additional benefit of providing calcium, another important plant nutrient, and is particularly useful when applied to groundnut. Elemental sulfur is also recovered during petroleum processing.

Sulphur is often the third least limiting nutrient in soils after N and P yet it is seldom included within available fertilizers. For example, widely available calcium-ammonium-nitrate (CAN), di-ammonium phosphate (DAP), Triple Super Phosphate (TSP) and urea do not contain S. Therefore, an important use for these sulphur-bearing agro-minerals is supplementation of imported mineral fertilizers that lack sulphur. In addition, impurities within these agro-minerals are often rich in plant micronutrients. Key components to wider use of these sulphur-bearing agro-minerals include their recovery as industrial by-products.

Sylvite and feldspars. Relatively few deposits of potassium-bearing agro-minerals exist in Africa and those that do are not being exploited. The preferred agro-mineral source of potassium is sylvite, which is naturally occurring KCl salt (van Straaten 2002). One advantage of this agro-mineral is that it may be used in its raw form and its processing requirement is simple crushing. Large deposits of sylvite occur in the Republic of Congo, Eritrea and Ethiopia (Table 3.2). A potash deposit in Congo was mined for several years, producing up to 450,000 tons per year, before it flooded in 1977. The deposits in Eritrea and Ethiopia are remote and not yet exploited. Smaller deposits of potassium-bearing agro-minerals also occur in Madagascar, Malawi and Uganda. Glauconite was discovered near Namibe in Angola, but little additional information is available about this potassium-bearing deposit.

Other potassium-bearing agro-minerals include feldspars and micas but these widely-distributed materials are low in K, not readily solubilized, and may be considered more as a soil conditioner than a source of nutrients. The indirect benefits from potassium released by these minerals are enormous as they are steadily weathered into soils. Consequently, acute potassium deficiency is relatively rare in clays and loams, other than highly-weathered oxidic soils, and is seldom expressed unless other more limiting plant nutrients are raised to more optimal levels.

Salt peter (Nitrate). Nitrogen-bearing agro-mineral reserves, particularly salt peter (sodium nitrate) are rare in Africa. One exception is the occurrence of nitrates in diatomaceous silts near Lake Turkana in Kenya. These nitrate reserves are vast, covering 0.6 km^2, and thick (10 to 32 m), and contain between 1.1 to 7.5% nitrate. This deposit is of slightly lower quality than those exploited elsewhere. For example, deposits exploited in Chile contain up to 10% nitrate. Nonetheless, exploiting nitrate deposits could prove a boon for Africa suggesting that further exploration of additional deposits in north Kenya and Southern Sudan is needed.

Guano. Deposits of guano result from the long-term activities of birds and bats, and occur on isolated islands and in caves. Guano is rich in nitrogen, phosphorus and other plant nutrients and may be applied to soils without further processing. Bat guano in Makindu, Kenya varies from 7% to 13% nitrogen and 3% to 6% phosphorus. Seabird guano deposits on offshore islands near Madagascar contain 14% P and 34% Ca, but much of the nitrogen is lost. Semi-fossilized guano on off-shore islands result in biogenic phosphate rock deposits containing 16% P and 40% Ca and occur in deposits up to many hundred thousand tons. Guano recovery is conducted in Namibia by erecting roosting platforms for seabirds and recovering their droppings, resulting in 2,150 tons of organic fertilizer per year.

The recovery of guano has important environmental and health concerns. Many small ocean islands serve as guano deposits resulting from sea birds. Mining guano from these seabird deposits may have serious negative environmental impacts on the birds themselves and surrounding marine life. Some guano deposits accumulating in bat caves are associated with histoplasmosis, an incurable fungal infection of the lungs. This condition is no trivial matter and those recovering guano from such caves must be rigorously protected. In general these infested caves are well known among the local population and whether identified as harboring histoplasmosis or simply attributed to evil spirits, care must be taken in the exploration and recovery of guano from them.

Other agro-minerals. Other agro-minerals serve to improve soil physical properties rather than supply nutrients. Examples of these soil conditioners include peat, ground silicates, zeolites, perlite, vermiculite and pumice. These materials are particularly important in the blending of rooting media for seedling and horticultural operations but will not be considered in depth within the context of ISFM. We note that one innovative use of pumice reported for Ethiopia's Rift Valley involves rock mulching as a means of soil and water conservation (see van Straaten 2002).

Integrated use of agro-minerals

A fundamental approach toward ISFM involves reliance upon biological nitrogen fixation (BNF) to provide nitrogen and minerals to furnish phosphorus and the nutrient bases K, Ca and Mg. BNF serves as either a direct source of N to symbiotic crops, or as an indirect source through decomposition of legume residues. Agro-minerals, on the other hand, are well suited as sources of P, Ca, Mg and S. Other required nutrients, particularly K, are best supplied in fertilizers. Micronutrients often occur as non-quantified contents within many agro-minerals and fertilizers. Given the widespread coverage of macronutrient limitations, micronutrient deficiencies are not particularly common (Bouis *et al.* 1999) and best addressed through direct mineral application (see Chapter 11). Furthermore, most crops, other than symbiotic legumes, respond well to supplemental top-dressing with nitrogen fertilizers. This overall nutrient supply strategy is referred to as "N from the air and others from the bag" that offers flexible adjustment to local conditions and opportunity for optimizing the use of locally available agro-minerals.

Several simple techniques may be employed to improve the availability of agro-minerals (van Straaten 2002). For example, partial acidulation is achieved by mixing PR with acid and can be performed using a cement mixer. Field trials conducted by IFDC have demonstrated that partially-acidulated PR at 40-50% acidulation with sulphuric acid approaches the effectiveness of P fertilizers (Chien and Menon 1995a,b). Blending PR with more soluble phosphate fertilizers and adding other nutrients such as urea and KCl has also shown promise in many areas of SSA (Chien *et al.* 1987).

Biological solubilisation relies upon plant roots or P-mobilizing microorganisms to enhance the dissolution of PR as a means of improving use efficiency and crop production. Many legumes are able to promote PR dissolution through the release of organic acids by their roots. In rotation systems, this then facilitates improved P availability to a subsequent cereal. Vanlauwe *et al.* (2000 a,b) showed significant yield increases and P utilization by maize following a legume supplied with less reactive Togo PR, relative to PR directly applied in a sole maize cropping system. Use of soil inoculants as biological activators is less established but offers potential for more efficient agro-mineral use (Carr *et al.* 1998). For example, Babana and Antoun (2006) demonstrated that inoculation with a combination of PR-solubilising microorganisms and a commercial arbuscular mycorrhizal fungus into a Malian soil applied with Tilemsi PR resulted in a 35% increase in P uptake and a 42% increase in wheat grain yield. Many 'new age' products claim to promote biological activation of mineral nutrients but their effects are poorly documented. There is a proliferation of products appearing on the market in sub-Sahara Africa (SSA) that claim major impact in increasing crop productivity. Some of these have a proven scientific basis while others cannot stand up to scientific scrutiny (see Chapter 6).

Another practical use of agro-minerals is through fortified composting. Applying agro-minerals, such as lime and phosphate rock, accelerates decomposition of composting organic residues which in turn produce organic acids that further solubilize the minerals. The finished product is a compost that is richer in both humus and plant nutrients. Furthermore, fortified composting permits better use of organic resources that are very low in nutrients, particularly cereal residues that might otherwise be discarded or burned (see Chapter 4). Ndung'u *et al.* (2003) describe a simple layering procedure for producing batch fortified compost within four months that results in an organic fertilizer containing 22 kg N, 4.2 kg P and 14 kg of K per ton, levels that are almost twice that of conventionally prepared compost (see Chapter 4).

Nutrient replenishment with agro-minerals

The largest approach toward the deployment of agro-minerals in Africa involves nutrient replenishment campaigns (Buresh *et al.* 1997). Small-scale farming has resulted in a continuous and massive loss of nutrients from soil amounting to 4.4 million tons of N, 0.6 million tons of P and 3 million tons of K per year from 201 million ha of cultivated land (Smaling *et al.* 1997). Crop decline from this nutrient depletion not only affects the viability of individual farms but the food security of sub-Saharan Africa. Soil fertility replenishment seeks to replace these lost nutrients through a combination of public and private investment. One strategy developed for East Africa involves the addition of 400 to 800 kg of finely ground phosphate rock per ha to be extended to farmers in severely P-deficient areas as a means of replacing twenty years of nutrient loss. This intervention is reinforced by increased cultivation of symbiotic legumes and agroforestry trees as a source of organic nitrogen (Giller *et al.* 1997). Other nutrient deficiencies are met through annual application of fertilizers. Interventions at this scale could deploy 4000 tons of phosphate rock to clusters of grassroots groups and farmer organizations covering 5000 households, provide improved, inoculated legume seed for planting and establish new market opportunities for the resulting crop surpluses.

While conceptually elegant, such replenishment efforts have failed to emerge during the decade since they were first proposed, in large part because of difficulties in defining the financial responsibilities of individual farmers, national governments and donor organizations. Clearly, if a small-scale farmer could afford full nutrient replenishment they would be well advised to do so but this scale of investment requires incentive and possibly subsidy. Furthermore, replenishment programs compliment farm input market development as they increase demand for agro-minerals and result in new opportunities for their profitable mining, processing and distribution as well as the local marketing of accompanying technologies.

Nutrient replenishment may be conducted on a smaller scale as well. Inexpensive packages containing fertilizer, PR and seed (PREP-PAC) were developed and distributed to smallhold farmers in West Kenya for treatment of severely P-deficient patches expressed in farmers' outfields (Okalebo *et al.* 2006; Woomer *et al.* 2002). Farmers were able to replace 10 to 30 years of P losses while obtaining a benefit to cost ratio of 1.3 to 1.6 in the first season. Test marketing of the product by agro-dealers in P-deficient areas, however, found that they were unable to derive expected profits without placing the PREP-PAC beyond the reach of poorer farmers ($0.67 per 25 m^2 patch or $268 per ha).

Localized mining and processing

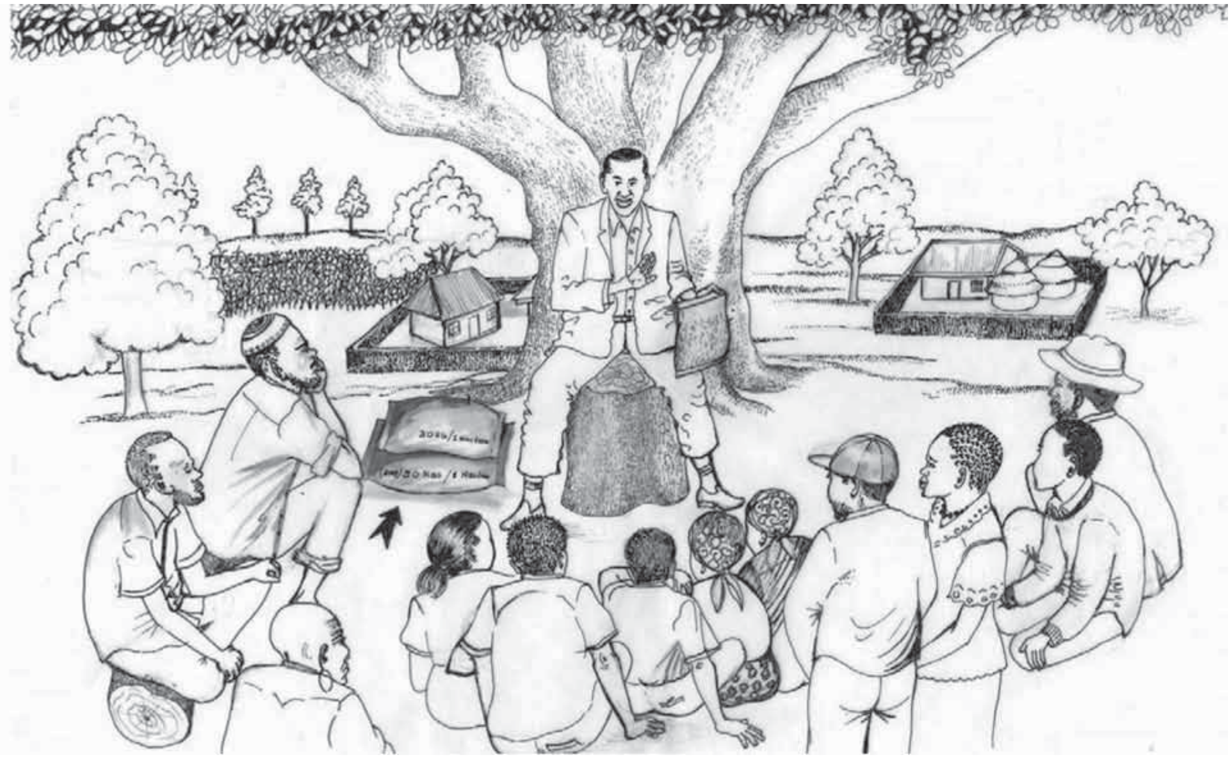
For sub-Saharan Africa to achieve targeted increases in fertilizer use and greater self-sufficiency in fertilizer production requires industrial scale exploitation of its largest agro-mineral deposits, but this does not preclude more localized efforts of mining and processing (Morris *et al.* 2007). Rather, smaller agro-mineral deposits require different mining and processing techniques. It is not unusual for deposits of soft phosphate rock or weathered limestone to be near P-deficient, acid soils. The challenge is to identify which deposits hold the greatest potential and to identify size-adjusted approaches toward their utilization.

Several smaller-scale mining technologies are already in place including locally fabricated stamp and ball mills presently in use by gold miners. Smaller concrete mixers may also be used to acidulate phosphate rock or to coat or blend agro-minerals and fertilizers. Furthermore, smaller-scale operations have several distinct advantages including 1) lower capitalization expenses, 2) shortened interval between geological discovery and mining operations, 3) strong incentive for local innovation and entrepreneurship and 4) greater reliance upon readily-available manual labor. In some cases, the recovery and preparation of agro-minerals can be conducted by farmers themselves during the off-season. Van Straaten (2002) estimates that small-scale extraction and processing of agro-minerals costs between $5 and $40 per ton depending upon access and characteristics of the deposit.

What remains lacking is the policy and marketing environment to stimulate more localized exploitation of smaller agro-mineral resources. Too often, small-scale mining is treated as an informal or even illegal activity, unsupported or punished by local authorities. This attitude must change for the sector to flourish. Mining ventures must be formalized and mineral rights secured. Mining and processing equipment must not be excessively taxed. Miners must be instructed in safety and processing procedures. Product standards must be set and enforced. Input suppliers must be informed of the value and profitability of agro-mineral trade and farmers must become aware of their use through substitution for more expensive fertilizer inputs.

Africa is rich in agro-mineral deposits of many types but has been slow to utilize them for the benefit of its farmers. It is well established which deposits have potential to meet the nutrient requirements for African agriculture, but not necessarily how to recover and mobilize these resources. In part, every agro-mineral deposit is unique and requires best management practices, and this expertise is not widely available in Africa. Indeed, agro-mineral resource development is not a well established field and is incompletely built into national development plans. This shortcoming is expected to change as the demand for crop nutrients grows in accordance with increased food production and expected improvements in living standards. In the near future, agro-mineral development has potential to have positive effects on many African economies, providing local employment, stimulating industrial innovation and reducing dependence upon limited foreign reserves presently used to import mineral fertilizers.

Agro-mineral development is not without risks. Most agro-minerals are benign and pose no health risk to those who mine and process them, however, there are exceptions. Several agro-mineral deposits derived from secondary and sedimentary geological processes contain cadmium, uranium and other heavy metals. These heavy metals pose a much greater risk to miners and processors exposed to them on a daily basis than to farmers who use them once or twice a year (van Straaten 2002). The health risk of histoplasmosis in guano caves was raised earlier in this chapter and must not be overlooked. Environmental hazards are also associated with the disposal of agro-mineral processing wastes, particularly their dumping into rivers and oceans. Again, the environmental impacts of recovering seabird guano from small islands can have a devastating effect upon surrounding marine ecosystems. Exploiting peat deposits contributes to atmospheric greenhouse gasses. At the same time, these hazards must be held in proportion, and addressed within sound agro-mineral development planning rather than used as a reason not to develop these resources. African farmers desperately require greater access to nutrient resources to address the needs of agriculture and the sooner that these naturally occurring nutrient reserves are harnessed, the better for Africa's nations and their citizens.



Chapter 4. Organic resource management

Organic resources are abundant in Africa because they are derived from both cultivated and natural lands, but they are under-utilized within the context of ISFM. Indeed, the availability of organic resources as nutrients sources is limited by their alternative uses as fuel, feed and fibre, and the labor required to collect and process these materials. Plant residues and livestock manures decompose rapidly in moist and warm climates, causing nutrient release to be poorly timed with crop demand (Myers *et al.* 1994), suggesting that the timing and placement of organic resources must be carefully considered. In many cases, organic resources most available to farmers have low nutrient concentrations (Vanlauwe *et al.* 2006) with limited potential to improve crop yields when applied as the sole source of nutrients. In contrast, alley farming has been widely tested in the tropics for its potential to sustain adequate food production under low external inputs. Large quantities of N are harvested from hedgerow prunings (≈300 kg N ha^{-1} yr^{-1}) but N contribution to crops is commonly in the range of 40-70 kg N ha^{-1} $season^{-1}$. This represents about 20% of N applied as prunings, however, N recoveries as low as 5-10% have been reported (Vanlauwe *et al.* 2006) and labour shortages reduce the willingness of farmers to adopt this technology (Ong and Black 1995). Within most smallholder communities, the demand for animal manure is usually greater than its limited supply and in pastoral areas with substantial livestock, free grazing poses difficulties in collecting and transporting this important organic resource (Lekasi *et al.* 2003). These difficulties must not preclude the use of organic materials as inputs to soil but rather require that they be utilized in more labor efficient and cost effective ways.

Meeting even modest food production and rural development objectives in sub-Saharan Africa demands strategic use of limited available resources (Savala *et al.* 2003; IFDC 2002). Even when the goals established by the Africa Fertilizer Summit (2006) are realized, the application of only 50 kg nutrients per hectare is very moderate compared to the quantity of nutrients needed under intensive crop production. ISFM interventions therefore aim to increase crop production through improving the agronomic efficiency of applied nutrient inputs. This approach necessarily involves the use of farmer-available organic resources and appropriate agronomic practices adjusted to local conditions as a means of both delivering nutrients and improving the efficiency of applied mineral fertilizers. These practices require informed actions by land managers because they must be adjusted to site-specific conditions. For this reason, ISFM is best achieved through the application of flexible principles that increase the availability of organic resource to farmers and makes best use of items.

Organic resource quality

Although use of organic inputs is hardly new to tropical agriculture, the first seminal analysis and synthesis on the decomposition and management of organic matter was contributed by Swift *et al.* (1979). This work established a conceptual framework for understanding the decomposition of various organic materials that involves soil and surface organisms, the physical environment and the chemical characteristics of a given substrate. These interactions in turn regulate mineralization and nutrient release during decomposition and transformation into soil organic matter (Woomer *et al.* 1994).

The nutrient contents of a wide range of farmer-available organic resources was characterized by the Tropical Soil Biology and Fertility Institute and other research groups. This information was entered into an interactive format, the Organic Resource Database (Palm *et al.* 2001) which may be accessed over the internet (server.ciat.cgiar.org/webciat/ORD). This database contains extensive information on organic resource quality, including macronutrient, lignin and polyphenol contents of fresh leaves, litter, stems and roots from almost 300 species utilized within numerous tropical agro-ecosystems. Data on the soil and climate from where the material was collected are also included, as are decomposition and nutrient-release rates for many of the organic inputs.

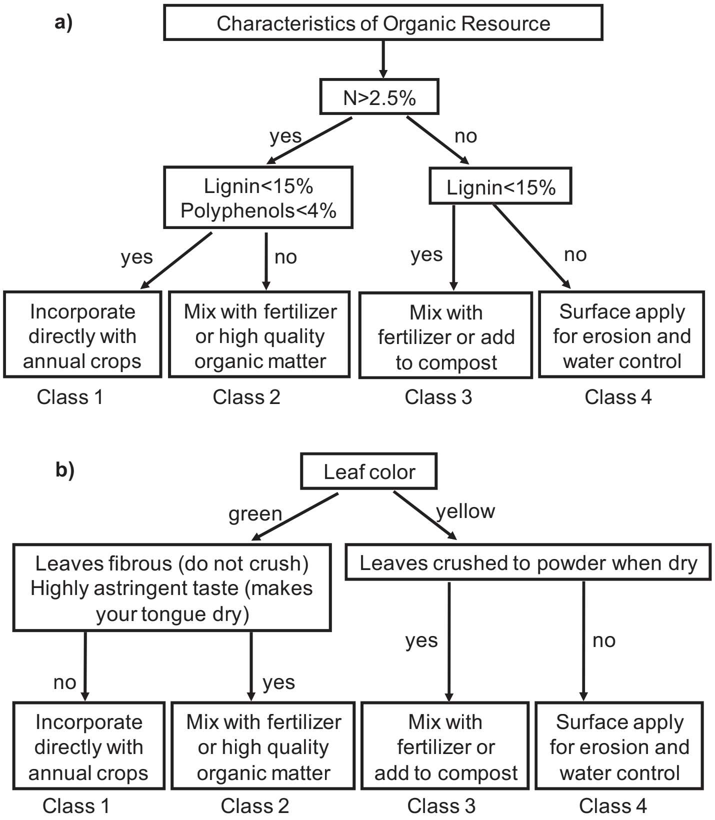


Figure 4.1 A decision tree to assist management of organic resources in agriculture. (a) is based on Palm *et al.* (2001); (b) is a farmer-friendly version of the same framework developed by Giller (2000).

Organic resources fall into basic categories of materials depending upon different rates and patterns of nutrient release associated with their chemical characteristics. These categories may be assigned from their N, lignin, and polyphenol contents (Palm *et al.* 2001). Based on this consideration, a simple decision tool for management of organic resources was formulated (Figure 4.1a). This system distinguishes four types of organic resources, suggesting how each can be managed for short-term nutrient release within cropping systems (Vanlauwe *et al.* 2006). Materials with less nitrogen and higher lignin and polyphenol contents are expected to release less nutrients due to microbial immobilization and chemical binding, and thus they require supplementary fertilizer or higher-quality organic resources to release nutrients at levels useful to land managers.

This conceptual approach was tested under field conditions in East, Southern and West Africa using biomass transfer to maize. The results clearly indicated that (1) the N content of organic resources are an important factor affecting maize production (2) organic resources with a relatively high polyphenol content result in relatively lower maize yields for the same level of N applied and (3) fertilizer equivalency values of organic inputs often equal or even exceed those supplied from inorganic sources. On the other hand, manure samples do not follow the general relationships followed by the fresh organic resources of plant origin. Manure behaves differently from plant materials because it has already been subjected a first-stage of decomposition when passing through the digestive system of animals, rendering the substrate less subject to nutrient immobilization. Organic resources applied to soils not only release nutrients, they enhance soil moisture conditions (Barrios *et al.* 1997) and improve availability of P in the soil (Nziguheba *et al.* 2000). In the long term, continuous organic inputs influence the levels of soil organic matter and the quality of some or all of its nutrient pools (Woomer *et al.* 1994; Vanlauwe *et al.* 1998; Cadisch and Giller 1997).

This diagnostic approach was later translated into a more farmer-friendly version (Figure 4.1b) using criteria that do not require chemical analysis (Palm *et al.* 2001). These characteristics include color (green versus brown), taste (mild versus astringent) and physical integrity (crumbly versus fibrous or solid). This approach provides land managers with the necessary knowledge to evaluate the potential use of organic resources in the field. On-farm studies suggest that a majority of plant resources available to land managers belong to Class 2 but several Class 1 materials exist that are considered to be as useful as fertilizer (Gachengo *et al.* 1999). This decision tree (Figure 4.1b) has been adopted by farmer field schools to make better use of organic resources under different conditions (Palm *et al.* 2001). Using this field diagnostic approach, farmers can confirm for themselves that the different organic materials have a predictable impact on crop yields and use them within their farms accordingly. Several organic resources and their chemical composition appear in Table 4.1. A more complete list of organic resources is presented in Appendix 1.

Farmer-available organic resources

Crop residues. Crop residues consist of the non-harvested portion of crop plants and are readily available to small-scale farmers as an organic resource. Crop residues are relatively low in nutrients and high in lignin (Table 4.1) and have competing uses as livestock feed, cooking fuel and structural or handicraft material. Within cereal-based cropping systems, the bulk of crop residues consists of cereal stover and legume stems and leaves. The amount of crop residues available at harvest is inversely proportionate to the crop harvest index. Harvest index is a common breeding objective but given the importance of crop residues, larger proportions of harvest do not necessarily benefit small-scale farmers who require these materials for other household needs.

Burning crop residues is sometimes practiced by larger farms as a means of waste disposal and field sanitation, but this management is discouraged among ISFM practitioners. Rather, crop residues fed to livestock improve the availability of manure, those applied as mulch offer protection to the soil surface and those incorporated with other, higher quality materials serve as substrate to composting operations. One difficulty in the management of crop residues as mulch is their loss from the feeding activities of termites and other soil macrofauna (Wood 1978, 1988), particularly when the material is transported by insects to nests beyond the root zones of cultivated plants. On the other hand, comminution of crop residues by fauna is a necessary first stage of nutrient recycling and the enriched soil forming termite mounds is available for localized use (Lavelle *et al.* 1994; Mapfumo *et al.* 2001).

In some cases, systematic misuse of crop residues occurs. For example, field legumes are often uprooted at harvest, piled in a nearby shady area and then shelled at leisure. The nutrient-rich fine fraction resulting from hand shelling is then deposited outside of the cultivated field. In many cases, even the resulting piles of legume trash remain unused, particularly when the material consists primarily of dried stems and roots and are unfit as livestock feed. Nonetheless, these materials may be utilized as mulch or in trash lines, or added to composts. Successful ISFM practitioners become attuned to taking fuller advantage of even small and obscure sources of organic inputs and finding ways to redirect them in an expedient manner. Selected crop residues and their nutrient contents appear in Table 4.1 and Appendix 1.

Green manure. Green manuring involves the cultivation of fast-growing leafy plants and their incorporation into the soil as a source of nutrients to succeeding crops (Hudgens 2000). This practice relies upon two basic mechanisms. Leguminous green manures are actively symbiotic and accumulate large amounts of biologically-fixed N. In addition, green manures establish litter layers and prolific root systems that serve as inputs to the following crop. Owing to their large accumulation of biomass and the threat of introducing a weedy competitor, incorporation of green manures is best practiced prior to seeding. For this reason, green manuring must be carefully timed to season and labor availability (see Chapter 6). In some cases, green manures provide nutritious fodders that complement bulky, less palatable cereal residues, and regular pruning may extend their lifetime in the field (Mureithi *et al.* 2002). Other benefits of green manuring include suppression of weeds, disruption of pest and disease cycles, maintenance of soil organic matter and improved soil porosity (Eilittä *et al.* 2004). Deeper rooting green manures also recover nutrients from lower soil horizons that would otherwise be lost to field crops (Jama *et al.* 1998; Shepherd *et al.* 2001; Young 1989; Gathumbi *et al.* 2003). Some species utilized as green manures include Dolichos bean (*Lablab purpureus*), *Mucuna* spp, Jack bean (*Canavalia*

Table 4.1. Mineral nutrient contents of some common organic resources (based upon the TSBF Organic Resource Data Base and other sources).

Material	Comment	N	P	K	Ca	Mg	lignin	polyphenol
		kg ton^{-1}						
Crop residues								
groundnut *(Arachis hypogaea)*	leaf	32.0	1.8	24.0	13.0	4.0	50.8	28.7
pigeonpea *(Cajanus cajan)*	pruning	24.0	1.5	12.0	5.7		150.5	52.3
soybean *(Glycine max)*	pruning	27.0	1.9	22.0			85.3	17.7
lablab *(L. purpureus)*	leaf litter	29.0	2.3	8.8	20.0	4.1	157.7	7.8
cassava *(Manihot esculenta)*	leaf litter	30.0	1.9	7.3	11.0	5.6	375.2	
rice *(Oryza sativa)*	straw	8.5	0.6	14.0	3.8	1.6		
bean *(Phaseolus vulgaris)*	stover	9.9	1.1	19.0	9.2	2.6	108.2	3.4
pea *(Pisum sativum)*	stover	14.0	0.8	11.0	14.0	2.6	82.0	16.0
sorghum *(S. bicolor*	stover	6.3	1.0	14.0	4.9	1.4	42.3	29.2
cowpea *(Vigna unguiculata)*	prunings	24.0	3.1	11.0	12.0	7.1	127.0	11.1
maize *(Zea mays)*	stover	8.3	0.8	13.0	3.4	1.9	88.2	7.4
Green manures								
Crotalaria spp	leaf	42.0	1.9	14.0	16.0	3.7	66.9	15.9
Desmodium intortum	prunings	22.0	1.5		5.2		164.9	113.3
Lantana camara	prunings	20.0	1.8	29.0	9.9		152.4	33.9
Leucaena spp	prunings	30.0	1.8	16.0	10.0	3.8	164.7	71.6
Mucuna pruriens	prunings	29.0	2.3	15.0	9.0	5.4	78.6	88.1
Tithonia diversifolia	leaf	38.0	3.8	46.0	20.0	4.1	116.6	34.6
Agro-industrial by-products								
coffee *(Coffea robusta)*	husk	17.0	1.3	29.0		1.8	3 9.6	13.8
rice *(Oryza sativa)*	husk	6.3	1.4	3.8	0.8	0.4	166.6	0.1
sugarcane *(Saccharum officinarum)*	bagasse	3.9	0.4	7.0	2.4	0.4	160.2	3.5
water hyacinth *(E. crassipes)*	whole plant	14.1	2.2	32.3	12.7	3.9	100	
Agroforestry species								
Acacia spp	leaf	25.0	1.7	11.0	7.2	2.4	144.5	99.6
Albizia spp	leaf	34.0	1.8	4.1	7.3	3.0	106.0	33.4
Calliandra calothyrsus	leaf	33.0	1.7	8.5	1 .6	3.1	165.5	94.6
Grevillea robusta	prunings	15.0	0.8	11.0	1.0	1.8	240.8	45.7
guava *(Psidium guajava)*	leaf	23.0	2.0	15.0	9.4	3.2	19 .2	138.6
sesbania *(S. sesban)*	leaf	35.0	2.1	14.0	18.0	3.6	5 .7	58.9

ensifornis), *Tephrosia* spp., and *Sesbania sesban.* These species are described in greater detail within Chapter 10.

Drought tolerant green manures are able to grow well into or throughout the dry season providing erosion protection from wind and off-season rains. Green manuring is distinct from cover cropping because it is intended specifically for soil fertility management but the species used for both strategies overlap (Lal 1997). Green manure is an actively researched and promoted technology, but one that is difficult for small-scale producers to adopt given their paucity of cultivated land and conflicting demands for labour. Nonetheless, it is a proven means of soil fertility restoration and maintenance that may prove relevant under many circumstances, particularly when linked to the rehabilitation of degraded soils. The nutrient contents of several green manure species are presented in Table 4.1 and Appendix 1.

Expectations from green manuring in Africa are somewhat tempered by disappointing experience. Green manuring with sunhemp (*Crotalaria juncea*), ploughed under when still green after only 60 days growth, was a standard practice for soil fertility management on commercial, large-scale farms in Zimbabwe (Rattray and Ellis 1952). The use of green manuring declined with the advent of mineral fertilizers and was replaced in rotations when soybean became an important grain legume crop. An example of mixed success with green manuring is the promotion of *Mucuna pruriens*, referred to as 'green gold', in Benin. Luxuriant growth of mucuna was effective in suppressing the pernicious grass *Imperata cylindrica* and rejuvenating the soil (Versteeg and Koudokpon 1990). The promotion of mucuna by research institutes and NGOs led to rapid uptake by thousands of famers (Versteeg *et al.* 1998; Eilittä *et al.* 2004). When promotion ceased, however, the use of mucuna declined rapidly to the extent that it is only seen sporadically in areas where it was previously common. In Malawi, *Tephrosia vogelii* was promoted intensively as a legume for under-sowing into maize during the late 1990s and seed of tephrosia fetched a price much higher than that of food legumes in the local markets (Giller 2001). A similar phenomenon has been observed in western Kenya with improved fallows of legume trees, where ICRAF claimed uptake by hundreds of thousands of farmers. The improved fallows have vanished since the intensive promotion by research and extension ceased. What was measured as farmer adoption was largely farmers producing seed of the shrubby legumes for sale (Kiptot *et al.* 2007). Thus evidence for uptake of legume green manures and improved fallows solely for improvement of soil fertility appears to be limited.

Animal manure. Livestock rearing is a near-universal smallholder enterprise that serves to accumulate wealth, generate income, improve household nutrition and provide sources of soil organic inputs as waste products. Manure may benefit land through two basic mechanisms. Grazing livestock deposit their waste products into the soil as they feed thus recycling nutrients from crop stubble, weeds and boundary plants. It is extremely difficult to recover manure remaining in the field following free grazing and much of its nutrients may be lost to runoff and volatilization. Alternatively, livestock may be periodically or permanently placed into stalls to facilitate the recovery of their waste products.

Many systems of agriculture revolve around livestock and their concentration of nutrients in manure. Use of cattle manure to fertilize crops was introduced by colonial agricultural officers throughout Africa, often at rates beyond the reach of modern day small-scale farmers. For example, the recommendation that 40 t ha^{-1} of kraal manure should be applied on land used for maize cultivation was issued in Zimbabwe in the 1920s, rates that were later adjusted down as mineral fertilizers became available. Fertilizer use recommendations in Kenya (KARI 1994) are compared to the expected results if 5 t ha^{-1} of cattle manure were applied.

Ring management systems of the savannah zone of West Africa result in the most fertile soils forming immediately around villages where manure is applied, then soil fertility declines in an outer ring of cultivation and increases again at greater distances due to less intensive cropping (Prudencio 1993). To the west of Lake Victoria in Bukoba and Tanzania, productive banana fields were situated in man-made islands of fertile soil, amidst large areas of infertile grassland (Milne 1938). The fertile soils around the homesteads were created through the concentration of nutrients in manure from large herds of cattle, and by the transfer of grass mulch. Since 1961, the area of grassland has shrunk by more than 40%, and the population of grazing cattle reduced by half, concomitant with a strong increase in human population and unequal distribution of resources. Declining productivity of bananas, coupled with a rapid shift to annual crops indicates that with current management the farming system has fallen below the sustainability threshold (Baijukya *et al.* 2005).

Another effective means of recovering livestock manure is to confine animals and regularly collect their waste. In many cases organic materials such as straws or wood shavings may be applied to the stalls for insulation and to absorb urine. Animals reject or drop some feed and this become mixed with the manure, urine and bedding to produce a combination ready for further composting. Alternatively, floors may be lined with concrete in manner that allows urine to be separated and applied to fields on a regular basis (Lekasi *et al.* 2003). Rearing small animals in

Table 4.2. The nutrient concentrations of selected manures available to small-scale African farmers.

Source	N	P	K	Ca	Mg	Lignin
	---------------------------------- kg ton^{-1} ----------------------------------					
Cattle manure	9.8	2.2	8.5	4.0	2.3	84.8
Cattle manure fresh	15.0	5.4	6.4			
Composted manure	18.2	10.0	15.1	30.6	5.7	76.4
Goat manure	15.0	4.0	5.3			
Pig manure	2.0	11.9	4.9			
Poultry manure	28.8	15.8	22.5	32.0	6.9	119.3
Rabbit manure	16.0	4.0	5.0			
Sheep manure	12.8	4.7	57.7	11.0	14.5	51.8

pens, such as poultry and rabbits, also permits ready collection and precise application of the waste products. Chicken manure consisting of feces, uric acid, feed refusals and bedding material may be mixed with low quality feeds and fed to cattle, a strategy that takes advantage of the higher digestive efficiency of ruminants. The nutrient contents of selected livestock manures appear in Table 4.2.

Agro-industrial by-products. Agro-industrial "wastes" result from the first-step processing of agricultural commodities. These by-products are potentially important sources of organic materials but pose difficulties for more distant small-scale farmers to access. In many cases, the agricultural raw materials are produced by small-scale out-grower farmers, transported to processing plants and then utilized by the central processing facility or nuclear plantation and not returned to the fields and farms of origin. Examples of these products include sugarcane bagasse, coffee husks, tea powder, rice husks and coconut husks. A selection of agro-industrial by-products and their nutrient content appear in Table 4.1 and Appendix 1.

One agricultural by-product with more localized importance is produced by millers that grind cereals into flour, resulting in bran. This nutritious material is generally fed to livestock. Aquatic weeds are another organic material that is available to farms near water bodies. Water hyacinth is an aggressive aquatic weed that has invaded many waterways of sub-Saharan Africa and must be periodically cleaned from harbors, dams and canals (Amoding *et al.* 1999). Pit composting of water hyacinth reduces moisture content from 92% to 25% and increases its nitrogen concentration from 1.9% to 3.4% on a dry weight basis (Muzira *et al.* 2003). This transformation greatly improves the economics of transporting this material to farmers fields (Woomer *et al.* 1999a).

Organic resource processing and application

Collection and storage. Organic resources may be either gathered and deployed, or collected and stored for use in a manner that is better timed to growing seasons and crop nutrient demands. Examples of direct deployment include the establishment of trash lines and mulches from crop residues and chopping and incorporation of green manures. Alternatively, organic resources may be collected, bulked and stored, practices that are particularly well suited to crop residues and animal manures. Examples of organic resource storage and use include piling crop residues as livestock feed during the dry season, heaping manures and the production of compost. It is important to protect stored organic materials from the elements, particularly excess rainfall, runoff and leaching. This goal may be achieved by covering organic heaps with tarpaulins or placing them in sheds. In many cases, organic materials must be well dried in the field and well aerated during storage to prevent further decomposition.

Table 4.3. The distance between 25 kg piles of organic resources necessary to achieve targeted levels of nutrients.

N content (%)	1.0	1.5	2.0	2.5	3.0
N per 25 kg pile (kg)	0.25	0.38	0.50	0.63	0.75
N addition per ha	--- distance between 25 kg pile (m) ----				
50	7.1	8.7	10.0	11.2	12.2
75	5.8	7.1	8.2	9.1	10.0
100	5.0	6.1	7.1	7.9	8.7
150	4.1	5.0	5.8	6.5	7.1
200	3.5	4.3	5.0	5.6	6.1

Pre-plant incorporation. One of the most expedient uses of organic inputs is to apply them during land preparation. This strategy combines organic input management with field operations such as tillage and fertilizer application. In the case of green manure, management precedes soil tillage by several weeks because vegetative cover must be chopped or grazed in order to reduce its bulk, particularly if tillage is to be undertaken by hand or animal traction

One important field operation is the spreading of stored organic materials such as animal manures and composts. One approach to allocating these materials within the field is to calculate the distance necessary between piles of known nutrient concentration that are required to obtain a targeted amount of nutrients. These piles are often distributed by wheelbarrow or in bags containing approximately 25 kg of organic inputs. Depending on the nutrient concentration and the targeted nutrient addition, these piles are spaced between 4 and 12 m apart from one another (Table 4.3). Land managers must learn to calibrate the placement of organic piles in the field, and their subsequent spreading to targeted rates of nutrient application. In addition, spreading and incorporation may be combined with pre-plant application of mineral fertilizers to simplify field operations. Caution must be exercised in applying low quality materials, even in conjunction with mineral fertilizers. Organic inputs extremely low in nutrients and high in lignin and polyphenols must not be incorporated into the soil as these inputs will likely result in immobilization of soil nutrients and applied fertilizers. Rather these materials are best applied as surface mulches.

Surface mulching. Surface mulching is a useful field practice in terms of soil surface protection and water use efficiency, but one that is difficult to achieve at a field scale (see Chapter 10). Crop residues have competing uses and are subject to rapid loss by termites and other soil fauna, and surface mulches subjected to rapid removal and comminution lose their intended purpose. Another source of mulch is prunings cut from boundary areas and nearby natural vegetation (Maundu and Tengnäs 2005) but this operation is labour consuming and the prunings are often better utilized on higher value crops, within animal feeds or as ingredients for compost making. On the other hand, near permanent soil cover is one of the foundations of Conservation Agriculture described in Chapter 10 and practitioners must find a means to gain access to sufficient organic materials. Establishment of trailing legumes as a relay intercrop is one means of producing live mulch that will survive into the following dry season and provide a surface mulch as leaf litter and dying stems and leaves (see Chapter 6).

Composting. Composting is a practical means of bulking organic resources and concentrating their nutrients. The composting process must be controlled, particularly through the choices of substrate, moisture content and aeration. It is characterized by a period of rapid decomposition and temperature accumulation followed by cooler, slower decay of the remaining organic substrate (De Bertoldi *et al.* 1985). The rate of decomposition can be increased by stacking the materials in a pile to a height of 1 to 1.5 m (Figure 4.2), however, taller stacks must be more regularly turned to facilitate rapid decomposition and prevent the formation of unwanted anaerobic by-products (Savala *et al.* 2003).

Table 4.4. Chemical characteristics of some compost samples submitted for analysis by farmers in Kenya (Lekasi *et al.* 2003).

	N	P	K	Ca	Mg	C	lignin	polyphenol
Source	kg ton^{-1}							
K.W. Kamau	12	3	20	38	5	350	107	42
C. Othiambo	16	11	11	35	19	410	84	32
M.K Ouma	20	6	2	18	3	320	131	6
P.S. Watua	26	7	24	16	7	550	222	38

The most important physical properties to composting are particle size and moisture content (Lekasi *et al.* 2003). Particle size affects oxygen movement into and within the pile, as well as microbial and enzymatic access to the substrate. Proper balance in the particle size should be maintained. If too large, the organic materials should be chopped into smaller pieces. On the other hand, if too small, the organic materials should be mixed with a bulking agent such as wood chips or bagasse. The optimum moisture content for composting is 40 to 60% as excess water interferes with oxygen accessibility, slowing the rate of composting. Too little water hinders diffusion of soluble molecules and microbial activity.

The relative quality and quantity of the organic residues affects the rates of composting and the characteristics of the finished products (Table 4.4). For example, when the carbon to nitrogen ratio (C/N) of the organic matter is about 25, transformation of the organic material proceeds rapidly with a high degree of efficiency of N assimilation into the microbial biomass. A narrower C/N ratio may lead to loss of N from compost through ammonia volatilization. Wider C/N ratios (>40) promote immobilization of available N in the compost, slowing the rate of decomposition. Therefore, addition of mineral N (and P) can enhance more rapid decomposition and enrichment of the low quality residues.

Low quality organic materials such as maize stover or wheat straw with a wide C/N ratio are suitable for preparing fortified compost (Ndung'u *et al.* 2003). The procedure for fortifying such organic materials follows.

1. Chop crop residues to 30-45 cm length to increase their surface area.
2. The chopped material is placed in five layers of 30 cm high by 2.0 m wide by 25 m long (≈500 kg in each layer).
3. At every 30 cm layer, evenly broadcast 4 kg DAP (or any other nitrogen-bearing fertilizer) for fortification lowering the C/N ratio from about 80 to 12.
4. Spread 1 kg of organic soil such as farmyard manure or sugar mill filter mud to serve as a microbial activator.
5. Apply 20 liters of water to enhance dissolution of fertilizers and to moisten the stover for microbial activity.

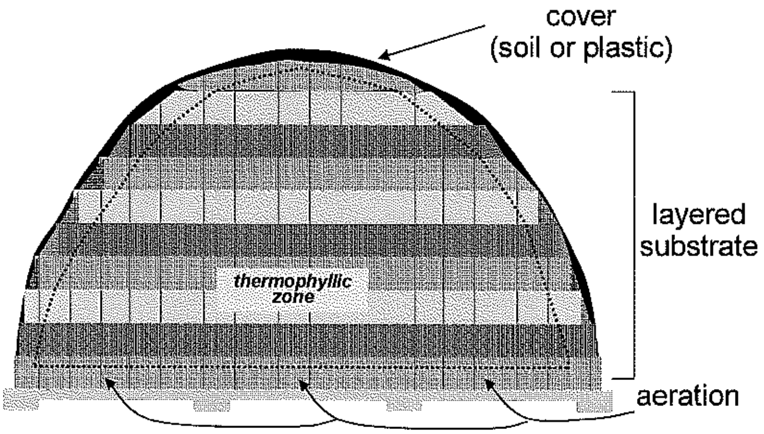


Figure 4.2. The principle elements of a compost pile including the interior thermophilic zone.

6. This process continues stepwise until the stack reaches 1.5 m (Figure 4.3).

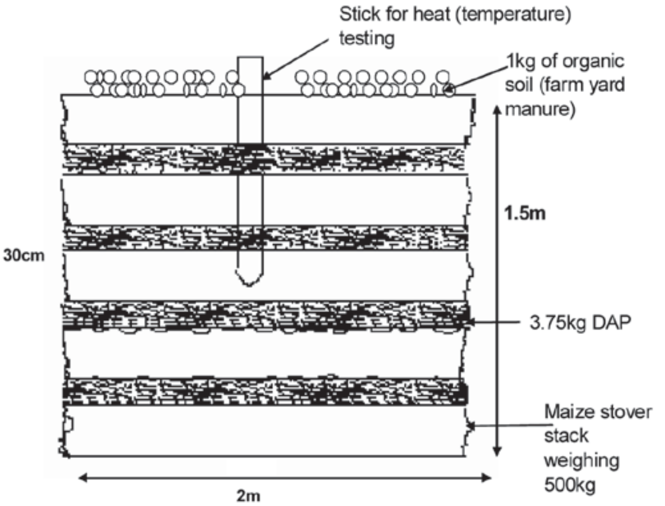


Figure 4.3. Producing fortified compost involves stacking different quality organic and mineral resources.

An alternative approach to composting involves epigeic earthworms, ones that live within and consume plant debris (see Chapter 5). These worms are domesticated and, when fed a variety of organic materials, they produce vermicompost. These composts are rich in plant nutrients and have excellent physical properties. Useful vermicomposting species include the tiger worm *(Eisenia foetida*) and African night crawler (*Eudrilus eugeniae*). The tiger worm is the most commonly utilized species in commercial vermiculture and waste reduction (Haimi and Huhta 1990). The species colonizes many organic wastes and is active in a wide temperature and moisture range. The worms are tough, readily handled, and survive in mixed species cultures. Night crawlers are a large prolific African worm that is ideal as fish bait and for earthworm protein production although it has poor temperature tolerance and handling capabilities (Viljoen and Reinecke 1992). *Perionyx excavatus* is another species well adapted to vermicomposting in the tropics that is prolific and easy to handle but it cannot tolerate temperatures below 5^0C. Vermicomposts are typically produced in raised beds that are well aerated, moist and covered using the following technique (Savala *et al.* 2003).

1. Prepare a bed with floor and walls 20-30 cm in height and line it with chicken wire for better handling and aeration Fill the bed with a 10 to 15 cm layer of coarse organic materials. Place another 5 to 10 cm layer of animal or green manure on top of the coarse material. The material must not contain poultry manure as uric acid is harmful to worms. Mix some of the finer material into the coarse layer. Moisten the organic materials prior to the introduction of the worms. Fresh materials need little watering while dried materials may require as much as 30 liters m^2.
2. Release the earthworms into the moist bed. Apply 200 to 300 adult worms per one square meter of compost bed. Avoid handling individual worms, rather place small handfulls of material rich in earthworms (clusters) into holes spaced about 0.5 m apart. Cover the bed with large leaves such as banana or dark polythene plastic. Frequently inspect the bed during vermicomposting for moisture and the presence of predators. Ants will usually leave the bed if the underlying chicken wire is violently and repeatedly shaken.
3. Organic materials may be applied to the bed regularly as additional layers or in discrete locations. A common practice is to provide organic wastes frequently by burying them in a different location within the bed. Vermicompost is ready after 2 to 4 months. Additional feeding prolongs the vermicomposting process but yields larger amounts of vermicompost. Withhold feed about three weeks before the vermicompost is collected to obtain "cleaner" finished compost.

Table 4.5. A comparison between inorganic fertilizers and organic inputs (after Woomer *et al.* 1999).

	Nutrient source	
Feature	Mineral fertilizer	Organic resource
Nutrient concentration	Higher and based upon labeled nutrient contents	Lower, unknown and variable between batches
Nutrient availability	Rapid chemical dissolution, subject to loss through leaching and sorption	Slower release, regulated and protected by soil biological process
Acquisition and cost	Costly, purchased in imperfect markets with limited opportunities for credit	Locally produced or gathered, often in short supply and with competing uses
Labour requirements	Easily applied and compatible with other field operations	Higher recovery and handling efforts, may interfere with field operations
Environmental impacts	Negative at excess rates, pollution of aquatic systems	Positive, favour carbon sequestration and soil biodiversity

4. When the vermicompost is ready, worms are harvested and compost processed. Place a fine feed material on the bed prior to vermicompost harvesting to facilitate the collection of worms. Wheat bran, brewers' waste or fresh cattle manure are particularly good feeds that lure earthworms. Collected worms may also be fed to fish and poultry. Spread vermicompost in the sun to collect other clusters of worms by hand as the vermicompost dries. Once worms are collected, the vermicomposting cycle may be repeated. The finished vermicompost is uniform, dark and fine textured.

Vermicompost is best used as the main ingredient in a seedling or potting medium after passing it through a 5-10 mm mesh. A typical nutrient content from a manure-based vermicompost using E. *foetida* is 1.93% N, 0.26% P and 2.64% K (Savala *et al.* 2003).

Combined application of mineral fertilizer and organic resources

A comparison of fertilizers and organic inputs is presented in Table 4.5. Within the context of ISFM, regardless of farm size and production objectives, it is important to combine organic and mineral sources of nutrients to obtain the full advantages of both sources (Giller 2002). Combining mineral fertilizer with organic inputs can substantially improve the agronomic efficiency of the nutrient use compared to the same amount of nutrients applied through either source alone (Vanlauwe *et al.* 2001a). Vanlauwe *et al.* (2001b) found positive interactions between urea fertilizer and green manure in combined application of 45 kg urea-N ha^{-1} and 45 kg green manure-N ha^{-1} resulted in a yield benefit of 0.5 t grains ha^{-1} compared to the application of either source alone (see Chapter 1).

Combined application results in improved agronomic efficiency for a number of reasons. First, common mineral fertilizers lack the minor nutrients essential for crop growth. Organic resources contain these, but to meet the crop's major nutrient requirements (N, P and K), often excessive application rates (more than ten tons of dry matter per hectare) are required if these

Table 4.6. Grain yield, N fixed and net N input for soybean varieties and subsequent maize grain yields in the Southern Guinea savanna of Nigeria (Sanginga *et al.* 2002).

	soybean grain yield (kg ha^{-1})	N fixed (kg N ha^{-1})	net N input (kg N ha^{-1})	following maize yield (kg ha^{-1})
IAC 100	1314	44	-8	1541
TGx 1519-1D	1340	78	11	2425
TGx 1456-2E	1494	69	15	3021
TGx 1660-19F	1493	103	30	1458
BR 17060	1136	92	43	1986
maize reference	-	-	0	1219

organics are the only input, and use efficiency of nutrients applied through organic materials alone is often low (Vanlauwe and Sanginga 1995; Cadisch and Giller 1997). Combining both sources enables supply of all nutrients in suitable quantities and proportions.

Second, a combination of inorganic and organic nutrient sources results in a general improvement in soil fertility status (Okalebo *et al.* 2003). An increased soil organic matter content enables improved nutrient retention, turnover and availability. Particularly P availability is enhanced by organic residue application (Nziguheba *et al.* 2000). Organic amendments also counteract soil acidity and Al toxicity (Pypers *et al.* 2005). The physical soil structure is improved, leading to reduced erosion, enhanced water infiltration and storage (Hudson 1994), and improved root development.

Practices to enable efficient fertilizer use do not necessarily require that the organic resources be applied at the same time. In addition, soil organic matter can be increased within the system through mineral fertilizer alone when their use results in much greater root biomass and return of crop residues. An example is the inclusion of a promiscuous, high-biomass yielding soybean into maize-based systems. On P-fixing soils, P addition is essential to stimulate N fixation by the legumes and enable sufficient biomass production. Vanlauwe *et al.* (2006) demonstrated that in absence of P fertilizer, improved dual-purpose varieties grown in western Kenya were unable to accumulate more biomass than the local soybean variety and P application doubled biomass yields. Sanginga *et al.* (2002) found significant positive rotational effects of soybean on a subsequent maize crop grown in rotation (Table 4.6). Rotational benefits not only included enhanced N supply to maize but other effects such as reduction of soil-borne diseases. N supply from BNF can complement N fertilizer application and improve soil fertility status. Combining mineral fertilizers with organic resources may result in greater nutrient use efficiency (Vanlauwe *et al.* 2006) but achieving this effect requires strategic management of fertilizers in terms of form, timing and placement as well as a sufficient supply of organic resources.

Table 4.7. Surface soil fertility of home and outer fields of a typical farm on a clayey soil in Murawe, Zimbabwe (Zingore *et al.* 2007a).

	organic C (%)	soil N (%)	available P (mg P kg^{-1})
home field	1.4	0.08	24
outer field	0.7	0.05	14

Improved nutrient use through local adoption of ISFM principles

Site-specific adoption of ISFM principles takes into account differences in soil fertility status within fields and farms and assures more efficient use of applied mineral fertilizers and available organic resources. The fields around the house or village are often much more fertile than the fields further away (Table 4.7). African farmers are excellent spatial manipulators of soil fertility, creating relatively rich and fertile islands by applying both organic and mineral fertilizers to the more accessible and secure fields, often at the expense of more distant fields and communal lands.

Decisions on fertilizer use and choice of cropping systems must be tailored to these differences in soil fertility and availability of organic resources. Zingore *et al.* (2007b) showed considerable differences in maize response to SSP fertilizer application between the home and outer fields of a typical farm in the Murawe smallholder farming area in Zimbabwe (Figure 4.4). A critical soil C content is required to obtain crop responses to fertilizer application. In fields with moderate C content, applying fertilizer accompanied by correct management strategies can considerably increase crop production. Some of the nearby fields are fertile to the extent that crops no longer respond to additional nutrients supplied through fertilizer but even in such fields, periodic application of a maintenance fertilizer dose is required to sustain yields. Distant fields are frequently infertile, depleted and have severely depressed soil organic matter contents. Farmers have little choice but to rehabilitate these fields through organic resource management because crops respond poorly to fertilizer application alone.

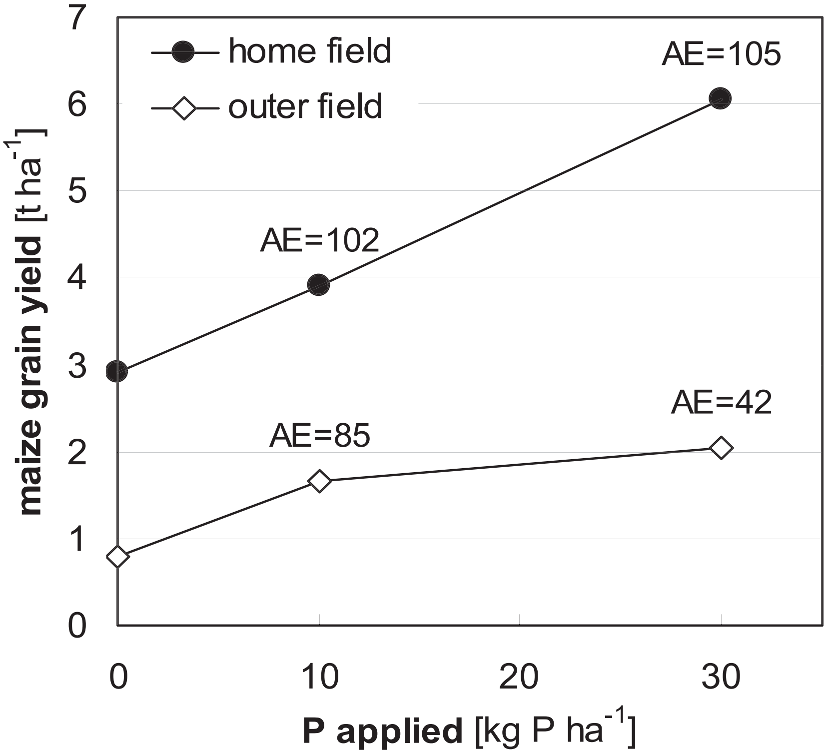


Figure 4.4. Maize response to SSP fertilizer application and AE in home and outer fields Murawe, Zimbabwe (Zingore *et al.* 2007b).

ISFM requires that farmers develop practical skills in the production, collection, processing and placement of organic resources. Different types of organic resources have various, and sometimes conflicting utility but practical field evaluation procedures are available to assist in their allocation. In some cases, the activities of soil biota clearly conflict with farmers' objectives in organic resource allocation but offer other, long-term environmental benefits. Estimating nutrient addition through the application of organic resources is more difficult than with mineral fertilizers, and their nutrient release patterns may be less predictable, but interactions between mineral and organic inputs tend to be strongly beneficial. Farmers must be conscious of organic resource allocation to the extent that some parts of the farm become degraded at the expense of other more accessible areas. Finally, skilled organic resource managers should not become confused with organic farmers as sometimes occurs by development agents and donor representatives as they operate under less prescriptive management guidelines and usually include manufactured mineral fertilizers within their soil management strategies.

Chapter 5. ISFM, soil biota and soil health

Soil biota are an essential component of soil health and constitute a major fraction of global terrestrial biodiversity (Moreira *et al.* 2008). Within the context of ISFM, soil biota are responsible for the key ecosystem functions of decomposition and nutrient cycling, soil organic matter synthesis and mineralization, soil structural modification and aggregate stabilization, nitrogen fixation, nutrient acquisition, regulation of atmospheric composition, the production of plant growth substances and the biological control of soil-borne pests and diseases (Woomer and Swift 1994). Understanding biological processes is not as well advanced as those related to soil physical and chemical properties, creating opportunities for breakthroughs in biotic function to better service agriculture. These services accrue through two basic approaches; indirectly as a result of promoting beneficial soil biological processes and ecosystem services through land management or directly through the introduction of beneficial organisms to the soil or crops, (Uphoff *et al.* 2006).

The concept of soil health is holistic and refers to more than just the vigor of soil biota. It also considers the chemical, physical, biological and ecological properties of soils, and the disturbance and ameliorative responses by land managers. Chemical properties refer to both nutrient supply and reduction of soil toxicities. Physical properties include soil structure and aggregation as they relate to nutrient and water retention and resistance to soil erosion. Soil biology examines not only the diversity of soil biota, but their biological functions as well. Soil ecology examines the interactions of soil biota with one another and their environment, and how soils operate as a habitat, both for soil organisms and plant roots. Soil health also describes the capacity of soil to meet performance standards relating to nutrient and water storage and supply, biological diversity and function, structural integrity and resistance to degradation. In this way, soil health regards soil as a complex and dynamic system that, in its best state, is able to support healthy vegetation and the larger needs of humankind. Conversely, soils may degrade, become nutrient depleted and under these conditions threaten rural livelihood and human wellbeing.

ISFM considers all of these soil services and how they interact from the standpoint of practical field operations and their effects upon land productivity. The most important of these manageable services include biological nitrogen fixation, other symbiotic and beneficial organisms, nutrient and moisture supply, carbon storage and protection from erosion. While ISFM has a strong economic and developmental focus, at its core it is committed to the improvement of long-term soil health. As soils are exploited, they degrade, especially when repeatedly cultivated without nutrient and organic matter inputs. This degradation has physical, chemical, biological components and is manifest within individual fields and farms, and across entire catchments and landscapes. Soil health may be considered an index of this degradation and recovery, and is thus an important consideration in assessing ISFM interventions. A framework for monitoring soil health within ISFM dissemination projects is presented in Chapter 14.

Beneficial soil organisms

Root nodule bacteria and biological nitrogen fixation. The nitrogen reserve of agricultural soils must be replenished periodically in order to maintain an adequate level for crop production. This replacement of soil nitrogen is generally accomplished by the addition of fertilizers or as products of biological nitrogen fixation (BNF). Symbiotic BNF allows many legumes to meet their nitrogen requirements from the atmosphere rather than the soil but in some cases, the resident population of rhizobium bacteria, the microsymbiont associated with nitrogen-fixing legumes, may not perform as an effective symbiotic partner. Increasing grain, tree and pasture legume production and matching these legumes with the correct microsymbiont are therefore a key component of improving agriculture and ecosystem services in the tropics. Identifying niches for legume BNF within existing farming systems is of paramount importance as the price of inorganic fertilizer increases. A key to ISFM is to promote BNF so that its products result in acceptable legume yields and offer residual benefits to following crops. The presence and effectiveness of rhizobia may be assessed by the abundance, size and interior coloration of root nodules. No nodules imply that the host's specialized rhizobia are absent from the soil. Sporadic, small nodules with white interiors suggest that infective rhizobia are present but are not symbiotically active. Legumes require inoculation when soil rhizobia are either absent or ineffective (Carr *et al.* 1998). Abundant, large nodules with red interiors indicate that the soil rhizobial population is healthy, at least for that specific legume. In general, legumes nodulated by the so-called 'cowpea miscellany' (*Bradyrhizobium* sp.) find symbiotic partners in most tropical soils, but they do not necessarily enter into vigorous N-fixing relationships with them. Over time, however, legumes enrich their soil environment with effective rhizobia. Legume nodules may be scored as absent, sporadic, abundant and, as occasionally observed, super-abundant and their interiors may be rated as white, pink or red. Experience is required in this evaluation because legumes have typically different nodule shapes and sizes and, as effective nodules age their interior color changes.

Nitrogen depletion in maize-based systems of West African savanna is estimated to be 36-80 kg N ha^{-1} per year (Sanginga *et al.* 2001b) and it has been obvious since the mid-1990s that fertilizer use is necessary if sustainable agricultural production in smallholder farms is to be raised to levels that can sustain the growing population. In contrast to expensive chemical N fertilizers, the use of nodulated legumes in smallholder farming systems is often a more attractive and practicable alternative. Their ability to fix atmospheric N allows them to grow in N impoverished soils. Maximal rates of BNF recorded in the tropics reach an astonishing 5 kg N ha^{-1} day^{-1} with the green manure *Sesbania rostrata* (Giller 2001). More than 250 kg N ha^{-1} of fixed N_2 has been measured in soybean in southern Africa with associated grain yields of 4 t ha^{-1}.

Assuming that only legume grain is harvested and crop residues are effectively recycled, net soil nitrogen accrual from the incorporation of legume residue can be as much as 140 kg N ha^{-1} depending on the legume (Giller 2001). This N tends to be released quickly when legume residues are incorporated into the soil and can contribute to substantial improvements in yield of subsequent crops. This N surpasses the 50 kg nutrient ha^{-1} fertilizer use across sub-Saharan Africa recommended by African Heads of States at the Fertilizer Summit held in 2006 and permits land managers to invest in fertilizer nutrients other than N.

The potential rates of BNF in legumes are most often not limited by symbiotic efficiency and sadly, less than 5 kg N ha^{-1} $year^{-1}$ is often fixed by grain legumes in smallholder farming due to other environmental stresses that restrict their performance. Attention is being paid to improving the BNF of useful legumes such as common beans, cowpea, groundnut, bambara, chickpea, pigeon pea and soybean. Forage and N-fixing trees and herbaceous legumes also play an important role in attempts to develop sustainable cropping systems in SSA. There is however a dearth of reliable estimates of N_2 fixation by these legumes under smallholder conditions and hardly any quantitative information is available on their residual N benefits to subsequent cereal crops.

Another group of root nodule bacteria that enter into nitrogen-fixing symbiosis with useful plants are *Frankia* spp., a filamentous *Actinomycete* that is associated with poplars and casuarinas, among others. These bacteria infect the host's root hairs or epidermus to form nodules that resemble swollen lateral roots or in some cases complex coralloid structures. In *Casuarina* spp., nodulation may be so prolific that they emerge from the soil or occur on stems (Giller 2001). By far, the greatest application of actinorhizal BNF is through the establishment of *Casaurina equisetifolia* in coastal, saline, dry and degraded lands. For example, over 12 million casuarina trees were successfully established along the northern coast region of Senegal to stabilize 22,000 ha of sand dunes, resulting in substantial carbon sequestration (Woomer *et al.* 2004). Casuarina was also planted as a pioneer species in a mined, fossilized coral bed near Mombasa, Kenya, producing a rapidly forming organic soil that permitted the introduction of other succeeding plants (Haller and Baer 1994). These successes are partly attributable to symbiotic BNF. Other potentially useful *Casuarina* spp include *C. cunninghamiana* and *C. glauca*, and species belonging to the related genera *Allocasaurina*, *Gymnostoma* and *Ceuthostoma.* These plants have highly reduced leaves, photosynthetic branchlets and cone-like fruits that lend a superficial resemblance to gymnosperms (Giller 2001).

Arbuscular mycorrhizal fungi. Arbuscular mycorrhizal fungi (AMF) are common root-colonizing fungi forming symbioses with most plants (Sieverding and Liehner 1984). These fungi have been reported from diverse natural ecosystems including deserts, sand dunes, tropical forests, salt marshes and in managed systems such as pastures, orchards and field crops (Brundrett 1991). Soil hyphal networks produced by these symbiotic fungi provide a greater absorptive surface than plant root hairs. In their turn, AMF benefit from carbohydrates provided by host plants as a source of energy. The value of AMF in extending the nutrient absorptive area of crop species has been thoroughly documented (Jacobson *et al.* 1992). Plant growth stimulation with mycorrhizal colonization is normally attributed to enhanced P uptake, although uptake of other nutrients in limiting supply may also be increased (Cooper and Tinker 1978). Mycorrhiza could be the most important untapped and poorly understood resource for phosphorus acquisition in agriculture (Johnson *et al.* 1991). While it has become widely accepted that mycorrhizal populations associated with roots of crop plants play a ubiquitous and critical role in phosphorus acquisition, our progress in utilizing this resource is incomplete. The fundamental reason underlying this disappointing progress is the lack of methodology suitable for identifying and evaluating mycorrhizal species and strains under field conditions.

Mychorrhizal symbiosis assists crops in recovering scarce reserves of soil phosphorus. In addition, mycorrhizal infected plants have been shown to have greater tolerance to toxic metals, root pathogens, drought, high soil temperature, saline soils, adverse soil pH and transplant shock than non-mycorrhizal plants (Johnson *et al.* 1992; Mosse *et al.* 1981; Bagyaraj and Varma 1995). Arbuscular mycorrhizal fungi therefore constitute one of the strategic interventions for ISFM. Two basic strategies to manage mycorrhizal fungi are available through optimizing crop and management practices that affect the abundance of indigenous mycorrhizae, or through the use of mycorrhizal inoculants.

Soil macrofauna. Soil microorganisms and smaller fauna (<2 mm in diameter) are largely dependent upon soil properties as a habitat, living in water films and void spaces. Larger soil invertebrates, referred to as macrofauna (>1 cm in length and >2 mm in diameter) have greater mobility and the ability to manipulate their environment. These organisms dig burrows or galleries and transport and mix organic resources that in turn affect the soil as a rooting environment for plants. The most important types of soil macrofauna in the tropics are earthworms, termites and litter dwelling arthropods, particularly millipedes. In many cases, soil macrofauna have developed mutualistic digestive systems with microorganisms that permit them to assimilate a wider range of low quality organic materials during gut passage. These feeding activities have profound short- and long-term effects on soil organic matter. During feeding, macrofauna fragment larger organic inputs and physically and chemically alter them through excretion, predisposing materials to more accelerated decomposition and nutrient mineralization by microorganisms. Earthworms, termites and millipedes each have different types of feeding strategies which in turn affect their impacts upon soil.

Because of their sensitivity to disturbance and their importance in redistributing and transforming organic inputs, soil macrofauna represent a important indicator of land quality (see Chapter 14). Soil macrofauna are recovered using a variety of methods including carefully collected litter and excavated soil monoliths, and in baited and non-baited pitfall traps arranged along transects within representative land uses (Bignell *et al.* 2008). Excavation of soil monoliths requires tedious hand sorting but produces quantitative results while pitfall traps are more rapidly deployed and recovered but results are best applied as indicators of diversity. In general, a large majority of macrofauna are recovered within the litter layer and top 20 cm of soil, but the timing of field observations is very important as many macrofauna become less active or migrate to deeper soil horizons during extended dry seasons. Once collected, macrofauna may be assigned to different taxonomic categories, or into trophic groups based upon their feeding behaviour.

Earthworms ingest mixtures of fine organic matter, microorganisms and soil, and deposit faecal materials with improved chemical and physical properties. They may be divided into three basic categories based upon their feeding and burrowing behaviour, epigeic, anectic and endogeic (Table 5.1). Epigeics live and feed in plant litter and have little effect on soil physical structure. Anectics and endogeics burrow into the soil with the former feeding on litter at the soil surface and the latter consuming soil organic matter and plant roots. Feeding by earthworms has a marked effect on the formation and partitioning of both soil organic matter and aggregates, while burrowing results in soil mixing and the formation of continuous void spaces. As a result, soils extensively worked by earthworms have lower bulk densities and higher rates of water infiltration and movement, but some cases of soil compaction by smaller earthworms are reported (Lavelle *et al.* 1994).

Table 5.1. An ecological classification of earthworms based upon habitat, feeding and physical characteristics (after Fragoso *et al.* 1997).

strategy	habitat	food	size and pigmentation
epigeic	lives and feeds in litter and surface soil	consumes leaf litter	< 10cm in length, highly pigmented
anectic	feeds on soil surface, burrows into surface soil	consumes leaf litter and surface soil organic matter	>15 cm in length, some anterodorsal pigmentation
endogeic	burrows within rhizosphere, surface soil to 80 cm depth	consumes root residues and soil with high organic matter content	10 to 20 cm or more in length, often non-pigmented

Termites feed on above- and below-ground litter and woody tissues and have adapted to a wide range of semi-arid conditions where earthworms are not found. Termite mounds are a distinctive feature across African savannas where termites forage a large proportion of annual aboveground biomass production. Some termites are associated with nitrogen-fixing bacteria while others culture fungi in their nests, two mechanisms that permit their feeding upon organic materials that are extremely low in assimilative nutrients (Lavelle *et al.* 1994). Not all termites build mounds but instead construct nests in soil, dead logs or in and around trees. Termite mounds are a more conspicuous feature, however, and may be domed, conical, columnar, mushroom-shaped or even cathedral-like and grow as large as 30 m across and 9 m in height (Lee and Wood 1971). As many as 1000 mounds may form per ha containing about 2400 tons of transformed soil. Termite nests, mounds, covered runways and galleries are constructed from organo-mineral pellets that are continuously eroded resulting in transfer between the soil surface and deeper horizons. The use of mounds as soil amendment depends upon the amount of termite mound material available and the nature of sub-soil that has been transported to the surface. In some cases mound soil results in markedly improved crop growth over surface soil and as much as 10 tons may be spread over the surface soil as an amendment. In others, particularly where sub-soils have toxic properties or where the surface soil is quite fertile, there is no advantage to spreading or cultivating the mounds.

Litter feeding arthropods inhabit the soil surface and surface horizon where feed is abundant, and commonly include millipedes and beetle grubs (coleopterans). Millipedes are extremely numerous in the Miombo woodlands of Southern Africa where they thrive despite consuming leaf litter of extremely low nutritional value. One means to compensate for this situation is to reingest fecal pellets after they are colonized by microorganisms, raising their nutritional value. Millipede populations of 282,000 per ha in a Miombo woodland consumed 6% of annual litterfall and deposited 327 kg faecal pellets ha^{-1} (Dangerfield 1990, Dangerfield and Telford 1991). While it is difficult to manage these excretions, they nonetheless play an important role in nutrient recycling in dry woodlands.

Plant Growth promoting rhizobacteria and fungi. Some non-symbiotic bacterial species living in the rhizosphere can affect plant growth either in a positive or negative way. Rhizosphere bacteria that favorably affect commercially important crops are grouped as Plant Growth Promoting Rhizobacteria (PGPR). The well known PGPR include bacteria belonging to the genera *Arthrobacter*, *Azotobacter*, *Azospirillum*, *Azoarcus*, *Bacillus*, *Burkholderia*, *Enterobacter*, *Klebsiella*, *Pseudomonas* and *Serratia* as well as *Rhizobium* on nonlegumes. They exert positive effects on plants through various mechanisms. Amongst the mentioned bacteria are those that directly cause plant growth promotion by producing and secreting plant growth regulators (PGRs) such as auxins, gibberellins and cytokinins, by eliciting root metabolic activities or by supplying biologically fixed-nitrogen. Consequently, germination, root development, mineral nutrition and water utilization are improved. Other PGPR operate through indirect mechanisms that involve suppression of bacterial, fungal and nematode pathogens. These include competition for colonization space and for nutrients, antibiosis, and excretion of volatile compounds, synthesis and adsorption of siderophores, excretion of lytic enzymes and induced systemic resistance.

Associative biological nitrogen fixation. Significant BNF occurs in the rhizosphere and the surface of roots through associative symbioses. In contrast to symbiotic BNF where defined root nodules are formed and the bacteria proliferate inside the plant, diazotrophic PGPR are not known to cause differentiation of plant organs, rather they cause proliferation of root hairs and root branching through plant growth regulators. BNF activities measured in cereals such as wheat, maize, rice and sorghum that were inoculated and colonized by *Azospirillum* and *Azotobacter* are low but not insignificant (Okon *et al.* 1994), and under certain circumstances, free-living diazotrophic bacteria associated with roots of non-leguminous plants can increase the growth and yield of crops (Boddey *et al.* 1991). Estimations of BNF by diazotrophs in the rhizosphere using various methodologies suggest that *Azospirillum* contributes about 5 kg N ha^{-1} year^{-1} to inoculated wheat, sorghum and maize (Boddey and Döbereiner 1994; Okon *et al.* 1994). This contribution is of minor importance, when compared to the application of nitrogen fertilizers, nevertheless, *Azospirillum* contribute to enhanced growth of their host plants, an improvement that is attributed mainly to root development.

The association of diazotrophic rhizobacteria with grasses is well documented (Baldani *et al.* 1997) and includes several bacterial genera and many important agricultural lands. Free-living diazotrophs are predominant in the rhizosphere of wheat (Heulin *et al.* 1994). Many agricultural grasses are associated with endophytic diazotrophic bacteria. They have mainly been isolated from plants in which significant BNF has been demonstrated, particularly in Brazilian sugar cane and rice cultivars but also in maize, sorghum, palms and coffee. There is a consensus that plant genotype is the key for obtaining a higher contribution of BNF in grasses (Burdman *et al.* 2000). Endophytic bacteria such as *Acetobacter diazotrophicus*, *Herbaspirillum spp.*, *Burkholderia spp.*, *Azoarcus spp.* and some *Azospirillum brasilense* are obligate or facultative endophytes that do not survive well in soil but spread readily on seeds and vegetative propagules.

Inputs of BNF to rice and sugarcane can be in the order of 10 to 80 kg N ha^{-1} year^{-1} (Boddey 1995). Occasionally, higher estimates were given such as that of Urquiaga *et al.* (1992) that reported up to 150 kg N ha^{-1} year^{-1} for a cultivar of sugar cane. The pairing of endophytic diazotrophs and the selection of plant genotypes may further improve BNF (Burdman *et al.* 2000), however, BNF in non-leguminous plants still warrants long-term research in order to be efficiently implemented.

Plant growth regulators (PGRs). There are many organic substances capable of regulating plant growth at very low concentrations by affecting physiological and morphological processes. When endogenously produced by plants, they are referred to as PGRs, phytohormones or plant hormones. The term PGR includes a large number of synthetic and naturally occurring compounds. Some soil microorganisms produce PGRs such as auxins, cytokinins, gibberellins, ethylene and abscisic acid that cause alterations in plant growth.

A diverse set of bacterial genera and species has been found to synthetize indole-3-acetic acid (IAA), including soil, epiphytic and tissue-colonizing bacteria. The observation that *Azotobacter*, *Azospirillum* and some strains of *Pseudomonas putida* produce IAA in culture, mainly when amended with tryptophan, suggest but does not necessarily demonstrate that this compound is produced within the rhizosphere. The size of the bacterial inoculum may determine whether the bacteria will either promote or inhibit root growth, reflecting the level of bacterially-produced IAA added to the plant (Okon *et al.* 1994). In maize roots inoculated with *Azospirillum*, relatively higher amounts of free active IAA were detected when compared to noninoculated controls (Fallik *et al.* 1989; Fulchieri *et al.* 1993; Lucangeli and Bottini 1997). It appears that the presence of *Azospirillum* and other rhizosphere bacteria may affect the metabolism of endogenous phytohormones in the plant. It is unknown however, if this phenomenon is due to free PGRs produced by bacteria or by elicitation or activation of plant hormones in the root tissue (Fallik *et al.* 1989; Burdman *et al.* 2000).

Biological control agents. A third group of PGP organisms is able to decrease or prevent the deleterious effects of phytopathogens (Lucy *et al.* 2004). Kinsella *et al.* (2009) reported the production of antibiotics in the rhizosphere by a strain of *Bacillus subtillis* and the importance of such production in plant disease suppression. Couillerot *et al.* (2009) showed that strains of *Pseudomonas fluorescens* and closely-related species have potential for biological control of root pathogens. Current genomic analyses of rhizosphere competence will likely lead to the development of novel tools for effective management of indigenous and inoculated bacterial biocontrol agents and a better exploitation of their plant-beneficial properties for sustainable agriculture.

Trichoderma is a fungus used for the biological control of fungal root pathogens that can improve plant growth in infested soils. Plants not infected with root pathogens often demonstrate a positive growth response after being treated with *Trichoderma* as well, suggesting production of a growth stimulant. Recently, this fungus was commercialized as a soil inoculant and seed treatment of agricultural crops with numerous commercial products being registered around the world. Other activities within the biocontrol field include the control of fruit pathogens such as *Botrytis*, as well as some recent work on the control of nematodes (Sharon *et al.* 2004).

Filamentous soil bacteria (*Actinomycetes*) also antagonize harmful soil organisms, influencing the microbial populations in the highly competitive rhizosphere (Emmert and Handelsman 1999). Some of these bacteria are potent biocontrol agents of plant diseases owing to their ability to exude a variety of antimicrobials and enzymes degrading fungal cell walls and insect exoskeletons (Weller *et al.* 2002). These bacteria also serve other plant beneficial functions in the rhizosphere. For example, some bacteria promote establishment of plant symbioses (Schrey *et al.* 2005, Tokala *et al.* 2002).

Phosphate solubilization. Solubilization of phosphorus in the rhizosphere is a common microbial process that increases the nutrient availability to plants. Phosphorus solubilizing microorganisms occur in most soils and comprise about 40% of the bacterial population (Richardson 2001). The ability of solubilizing microorganisms to mobilize phosphorus has been attributed to their ability to reduce pH by releasing organic acids such as citrate, lactase and succinate. These organic acids can either directly dissolve mineral phosphates as a result of anion exchange or chelate both Fe and Al ions associated with phosphate. Insoluble phosphorus is then converted into soluble monobasic (H_2PO_4) and dibasic (HPO_4^{2-}) forms. This conversion leads to an increased availability of phosphorus to plants (Gyaneshwar *et al.* 2002). Plant responses to inoculation with P-solubilizing rhizobacteria are reported but variable and difficult to reproduce (Richardson 2001) in large part because the bacteria may already be present within the soil in sufficient numbers to obscure a response to inoculation. Inappropriate laboratory screening procedures and poor understanding of plant-bacterium-soil interactions are impediments to successful deployment of P-solubilizing inoculants, nonetheless, some commercial products containing P-solubilizing microorganisms are available on the market.

Soil biological processes and land management

Enrichment of indigenous microsymbionts. The ability of beneficial organisms to survive in soil and plant debris during periods of heat and moisture stress is crucial to their ability to function under later, more favorable conditions. For example, in their saprophytic phase of their life cycle, rhizobia persist in the bulk soil, the decaying root nodules from previous symbiosis or in the rhizospheres of non-host plants and then readily infect legume hosts as their roots reappear (Bohlool *et al.* 1984). The ability of rhizobia to persist even within degrading soils maintains the BNF potential of smallholder systems and explains why it is often not cost-effective to inoculate promiscuously nodulating legumes (Sanginga *et al.* 2000). The population sizes of microsymbionts and mutualistic rhizosphere organisms are enriched through their association with plants and their residues, and this in turn permits them greater opportunity to survive periods of stress. Indigenous organisms are by definition acclimatized to the principle biotic and abiotic stresses within their environment but this ability does not preclude opportunity to introduce saprophytically competent beneficial organisms able to colonize new environments to the extent that reintroduction later becomes unnecessary (Lowendorf 1980). Furthermore, the ability of beneficial microorganisms to withstand environmental extremes usually exceeds that of their associated plants, due in part to their greater tolerance to salinity, extreme temperatures and acidity (Mendez-Castro & Alexander 1976).

Another approach to enriching highly effective indigenous microsymbionts is to select legumes for more promiscuous nodulation. Starting in 1978, plant breeders in Nigeria targeted the improvement of BNF by soybean through promiscuous nodulation with indigenous soil bradyrhizobia, seeking to eliminate soybean's need for inoculation (Sanginga *et al.* 2000). The program was based on selection of progeny from crosses between Asian and American soybean varieties exhibiting nodulation in local soils using visual scores for nodule mass (Kueneman *et al.* 1984). More freely-nodulating soybean varieties have also been selected through field trials in Zambia (Javaheri and Joshi 1986; Carr *et al.* 1998), Tanzania and Cote D'Ivoire. Currently, smallhold farmers in Nigeria, Zimbabwe, Kenya, and Zambia are widely adopting promiscuous soybean cultivars, in part because their semi-determinate flowering results in additional crop residues available for livestock feed or crop rotation. Nonetheless, some controversy surrounds whether or not indigenous nodulating rhizobia achieve their full BNF potential as many nodules formed on these lines tend to be small and have bacteroidal zones that are green or pink rather than the healthy red colour of leghaemoglobin. Attention is being paid to improving the BNF of promiscuous nodulating soybeans in an attempt to develop sustainable cropping systems in the moist savanna. There is however a dearth of reliable estimates of BNF by these promiscuous soybeans and hardly any quantitative information is available on their responsive to inoculation . A study by Sanginga *et al.* (1997) in the Southern Guinea savanna zone using the ^{15}N isotope dilution method to assess symbiotic BNF, response to inoculation and the N contribution of different soybean lines showed that rhizobial inoculation increased total N and grain yield of early maturing cultivars but did not affect the later maturing ones.

Crop and management practices affecting mycorrhizal abundance. In agricultural systems, edaphic factors, land use, cropping systems and management practices interact to influence AMF species composition and spore population. Consequently, changes in agricultural practices will inevitably lead to a change in the overall abundance of propagules of each fungus within a population (Abbott and Abbott 1989). As with legume nodulating bacteria, different strains exhibit varying degree in efficiency depending upon the combination of mycorrhizal species and host plants. Several studies have examined the effects of cropping sequence on mycorrhizal infection and spore populations. Harinikumar and Bagyaraj (1988) found that growing a non-mycorrhizal plant for one season reduced AMF colonization of the subsequent crop by 13% and a fallow period reduced colonization by 40%. Johnson *et al.* (1991) observed shifts in populations and species of AMF found in various sequences of maize or soybean rotation. Certain species were favored by the presence of maize and others by soybean.

Differences between maize and soybean could also be related to differences in mycorrhizal dependency of the two crops. Many crop plants show mycorrhizal dependency, defined by Gerdeman (1975) as "*the degree to which a host relies on the mycorrhizal condition to produce maximum growth at a given level of soil fertility*". Many cultivated legumes fall into this category (Tompson 1991). The selection of agriculturally important plant germplasm more tolerant of low P because of their greater dependency on AMF may increase productivity on P deficient soils common in SSA and reduce P fertilizer requirements. However, in agricultural breeding programs where selection usually occurs under conditions of high fertility, the resulting cultivars may have reduced symbiotic effectiveness. In so doing, breeders inadvertently select against crop performance in a low-input farming system. These cropping systems are currently practiced throughout SSA where legume cultivation serves as a potential source of nitrogen inputs. Symbiotic legumes require more P for their nodulation and N fixation processes, a requirement that results in P-limited conditions and greatly reduces biological nitrogen fixation. Improved mycorrhizal association offers a way out of this dilemma.

In general, legumes have a greater dependence upon mycorrhizal fungi for nutrient acquisition than do cereals but considerable variation occurs between species and cultivars (Khalil *et al.* 1994). For example, large differences in mycorrhizal infection were observed between the two promiscuous soybean cultivars grown in Zaria, Nigeria (Sanginga *et al.* 1999). This is an indication that considerable variability exists in the mycorrhizal dependence of promiscuous soybean cultivars when grown in farmers' fields and suggests that local mycorrhizal populations influence crop performance. Other investigations have found that crop species can positively influence AMF communities in the soil (Johnson *et al.* 1991). Because crops preferentially select for and enrich specific AMF species, cropping sequences directly influence their species composition. It is then critical to consider how the AMF species that proliferate within a particular cropping system affect crop production, particularly given their role in phosphorus solubilization and acquisition.

Land management and soil engineers. A practical means to obtain ecosystem services from soil macrofauna within cropping systems is to manage soils and organic resources in a manner that results in less disruption of their habitat. Minimium tillage permits complex food webs to develop within soil (Blank 2008) that more effectively recycle nutrients while intensive tillage results in a massive loss of soil macrofauna (Lavelle *et al.* 1994) and less desirable physical properties. Surface mulching provides valuable feed and habitat for epigeic and anectic macrofauna, although in the case of termites, their effects may not necessarily be beneficial. Practical success has been achieved in the area of earthworm recolonization and corresponding improvement in soil physical properties (see Chapter 10). Converting natural savanna to improved pasture increases soil macrofaunal biomass four-fold including an increase in fresh earthworm biomass from 39 kg to 412 kg ha^{-1}. Much of this increase appears related to the presence of pasture legumes and avoidance of pesticides (Decaëns *et al.* 1994).

Introduction of beneficial organisms

Inoculation with rhizobia. The first patents on rhizobial inoculation were filed at the end of the 19th Century shortly after the recognition that legume root nodules were the site of BNF by symbiotic bacteria, rather than pathological galls. Thus the concept of manipulating BNF by the introduction of strains of bacteria goes back almost 120 years (Eaglesham 1989). The three main producers of soybean, which also produce the largest amounts of rhizobial inoculants are USA, Brazil and Argentina (Saint Macary *et al.* 1993). Similarly, most of the inoculants produced in other countries are for use with soybean as the coverage of this crop expands. The soybean varieties that are cultivated by commercial farmers are specific in their nodulation requirements and compatible rhizobia are rarely present. In Australia, inoculants are also commonly applied to crop and pasture legumes because most of these legumes were introduced from other continents and indigenous rhizobia are absent, host incompatible or weakly symbiotic (Howieson *et al.* 2000; O'Hara *et al.* 2002). A similar trend in rhizobial population sizes was noted in the drier cultivated areas of East and Southern Africa (Woomer *et al.* 1997).

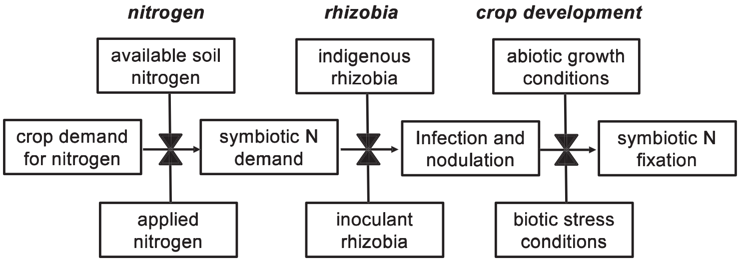


Figure 5.1. Factors regulating legume BNF may be used to predict where and when successful symbiosis will be established.

Nitrogen fixation by legumes results from a stepwise sequence of conditions and events that, if properly characterized, can permit reliable forecasting of where and when it will occur (Figure 5.1). Three situations can be identified when introduction of rhizobia is necessary to establish nodulation and effective BNF in legumes: 1) where compatible rhizobia are absent; 2) where the population of compatible rhizobia is too small to give sufficiently rapid nodulation; and 3) where the indigenous rhizobia are ineffective or less effective in BNF with the host legume of interest compare to elite inoculant strains. It is important to realize that observation of poor nodulation on a field-grown legume is not clear evidence that any of these conditions apply, due to the enormous number of environmental constraints which can also interfere with nodule formation and the difficulties of observing or recovering nodules on deeper roots. Potential benefits from inoculation are best assessed by conducting need-to-inoculate trials in the field where un-inoculated plots, inoculated plots and plots fertilized with substantial amounts of fertilizer N are compared (Date 1977; Sylvester-Bradley 1984; Vincent 1970). If growth of the legume is not improved by N fertilizer, then it is likely that other growth conditions are limiting (see Chapter 11) and that inoculation is unlikely to result in improvements in yield without accompanying technologies.

The likelihood of responses to inoculation can also be assessed by counting the population of rhizobia in the soil using an appropriate trap host (Woomer *et al.* 1990). If there is a small population of effective rhizobia (less than 20-50 cells g soil^{-1}) then it is likely that a yield response to inoculation exist (Singleton & Tavares 1986; Thies *et al.* 1991). A simple model (Figure 5.2) was developed to predict the likelihood of inoculation responses based on the N status of the soil and population size of indigenous rhizobia (Thies *et al.* 1991). However, although this method can demonstrate where responses to inoculation are likely, the presence of a large indigenous population of compatible rhizobia certainly does not preclude the possibility that responses to inoculation can be obtained if competitive and highly effective strains are introduced in high-quality inoculants. Such an example is observed in Brazil, where responses to re-inoculation resulting in soybean yield increases are observed even in soils with populations reaching one billion cells per gram (Hungria *et al.* 2005, 2006). If compatible rhizobia are absent, nodulation and BNF are likely to increase in proportion to the number of rhizobia applied in the inoculum (Brockwell *et al.* 1985, 1989).

The characteristics of indigenous rhizobia and the delivery of inoculants also affect host response (Singleton *et al.* 1992). Thies *et al.* (1991) suggest that indigenous populations of greater than 50 cells per gram of soil (or about 60 billion rhizobia per ha) may outcompete rhizobia introduced as seed inoculant. Others suggest that this threshold may be somewhat higher (100 to 300 cells per gram), but the principle remains the same, indigenous rhizobia, particularly those of reduced symbiotic potential, may pose an obstacle to BNF. To counter this competition from indigenous rhizobia and unfavorable soil conditions, land managers must deliver a minimum dose of inoculant rhizobia. A few hundred cells per seed is sufficient to result in infection by inoculant strains under favorable conditions, but it is possible to greatly exceed this dose (to many thousand cells) based upon the amount and population density of inoculants applied to the seed. The use of adhesive in seed coating greatly increases the number of inoculants rhizobia. Gum arabic, a product derived from *Acacia senegal*, is excellent for this purpose and widely available in SSA (Woomer *et al.* 1997). Other improvements in inoculant delivery are available, such as liquid formulation or pelleted inoculants, but these may be difficult to adjust to smallholder farming conditions as they were originally developed for mechanized planting systems.

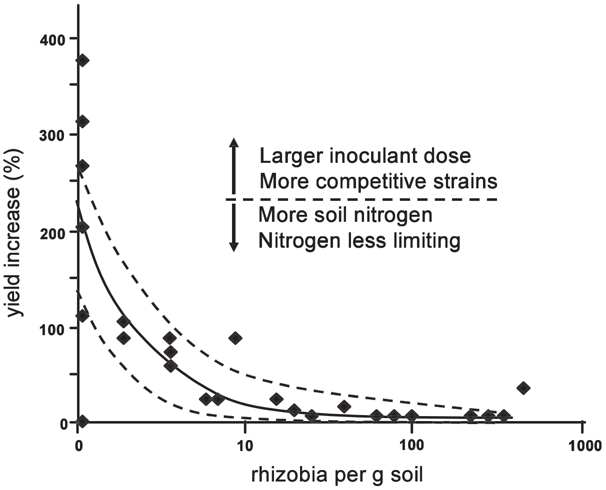


Figure 5.2. The population size of indigenous rhizobia affect observed inoculation response.

An assessment of rhizobia in soils of East and Southern Africa (Table 5.2) suggests that their population sizes vary between ecological zones and land use but often occur below the threshold that precludes legume response to inoculation (Woomer *et al.* 1997). Clearly, rhizobial populations in soil are greatly diminished within warmer, drier climates. Furthermore, while *Bradyrhizobium* sp. has widespread distribution, those that nodulate soybean are rare and few. The population sizes of rhizobia nodulating soybean fell far below the threshold of 50 cells per gram of soil in 94% of the locations examined. Sanginga *et al.* (1996) reported a large variability in nodulation and growth of mucuna grown in farmers' fields in the derived savanna of Benin. Nodulation did not occur in 40% of the fields, indicating a deficiency of compatible indigenous rhizobia.

Inoculation with mycorrhizal fungi. Commercial mycorrhizal inoculant are not yet widely available in Africa, although they have been in existence for several years. Alternatively, there are options for local, on-farm production of inoculant for specialized application in preconditioning tissue culture seedlings. Banana yield has declined in its traditional growing areas in Uganda and Kenya largely due to uncontrolled pests and diseases and declining soil fertility. Tissue culture plantlets offer an excellent means of providing pest- and disease-free planting material to farmers. Inoculation of tissue culture bananas with AMF can enhance their early survival through a substantially enhanced root network (Figure 5.3). The effect of AMF on plant growth and survival was consistent with observations eight weeks after planting and continued throughout the following 22 weeks. All plants inoculated with the *Glomus* species other than *G. albida* exhibited abundant mycorrhizal development while none of the non-inoculated plants were colonized. The mycorrhizal frequency and intensity of root colonization steadily increased with each harvest for all the other *Glomus* species (Figure 5.3). *G. etunicatum* and *G. intraradices* endophytes consistently had a higher level of root colonization in comparison to *G. mosseae*.

Inoculation with arbuscular mycorrhizal fungi shows considerable potential to enhance the growth of tissue-culture bananas. Bananas are highly dependent on their mycorrhizal association and demonstrate a degree of specificity, hence the importance of collecting arbuscular mycorrhizal fungi germplasm from banana plantations to screen for effectiveness on plant

Table 5.2. Indigenous *Bradyrhizobia sp.* measured in soils of different moisture regimes and elevations of East and Southern Africa (after Woomer et al. 1997).

moisture	elevation	
	lowland and midland	uplands and highlands
	-------- cells g^{-1} of soil -------	
semi-arid	10 to 27	4368
sub-humid to humid	23 to 177	74 to 3370

growth, nutrient uptake and control of root and soil borne pests and pathogens. Little is known on competiveness between various species or what governs their infections and effectiveness and it is therefore not possible to predict the effect of inoculation with a mycorrhizal inoculant based upon spore counts or species composition. There are, however, relatively simple procedures to test effectiveness of particular inoculants on crops making use of bioassays and using soil from the particular location of interest. Mycorrhizal infectivity is determined by the Most Probable Number method and can serve for comparative purposes (Porter 1979). The Mean Infection Percentage assay (Moorman and Reeves 1979) and the Infection Unit assay (Franson and Benthlenfalvay 1989) are also available as assessment tools.

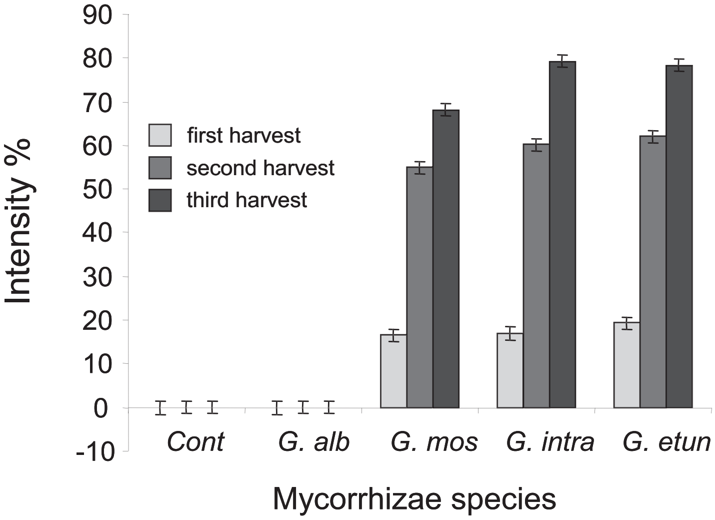


Figure 5.3. Infection intensity for banana after 8, 18 and 22 weeks following inoculation with four species of mycorrhizae (Jefwa, 2005. TSBF report to the Rockefeller, unpublished).

Introduction of earthworms and millipedes. Earthworms are widely distributed throughout the world but most of this introduction has occurred inadvertently through the transport of plants and soil. Numerous exotic earthworm species, such as *Dichogaster bolaui*, *Amynthas gracilis* and *Eudrilus eugeniae* have spread from their original restricted habitats to four or five different continents, and even displaced native species. One such species, *Pontoscolex corethrurus* originating from South America, was reported in 56 different countries, 94 natural ecosystems, 31 croplands and four types of organic wastes (Fragoso *et al.* 1999). On the other hand, many native species are difficult to raise even under laboratory conditions and have little potential for wider distribution.

Modest success has been achieved in the deliberate introduction of earthworms by those seeking to correct soil degradation or improve crop performance. In India, *P. corethrurus* was introduced into a tea plantation by releasing 350 g of worms into small pits enriched with organic and inorganic inputs. Within a few months, fresh tea leaf yields increased substantially (75 to 240%), and continued for ten consecutive harvests (Figure 5.4). While this yield increase is impressive, it is costly and requires that large amounts of earthworms be reared in vermiculture beds containing layers of soil, cattle manure and tea waste. These vermiculture beds are lined with plastic, drained of excess water and covered for shade, greatly adding to their cost of production. Earthworm introduction into production fields requires about 300,000 individuals per ha with 130 kg live weight costing about $4 per kg (Lavelle 1996)

A useful approach to rearing *P. corethrurus* in Peru involves the use of small (0.05 m^3) wooden frames containing mixtures of 1 part sawdust and 3 parts soil that can produce about 3100 worms per year at a cost of $10 per kg. These worms prove useful when added to containers in tree seedling operations but have little effect when inoculated into field soils, even when introduced at rates of 350 kg ha^{-1}. Earthworms did prove effective in restoring degraded lands in South America and on Caribbean Islands, but these gains were not considered to be economical given the high cost of earthworm rearing and introduction (Lavelle 1996). One proven earthworm technology involves the preparation of vermicompost using epigeic earthworms, particularly *Eisenia foetida*

(Appelhof *et al.* 1996; Savala *et al.* 2003). The production of vermicompost is described in further detail within Chapter 4.

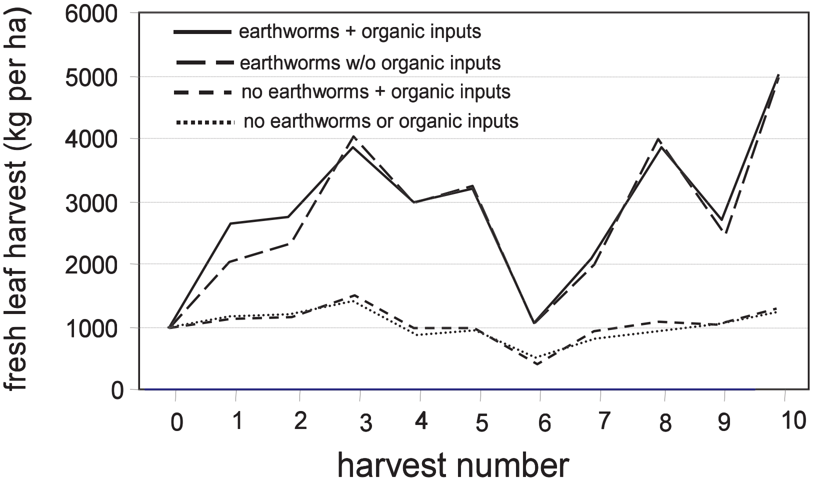


Figure 5.4. Monthly green leaf tea production following introduction of earthworms and organic inputs at the Sheikamuli Tea Estate, Tamil Nadu, India (after Lavelle 1996).

Another successful introduction of macrofauna involves millipedes in Kenya. Bamburi Cement Limited began operations near Mombasa in 1954, mining a fossilized coral reef as raw material in quarries that later extended for 6 km. Excavation for the coral limestone extended to just above the saline groundwater and no soil was readily available for re-vegetation of the abandoned quarry floors. Land rehabilitation began in 1971 with efforts that included establishment of *Casuarina equisetifolia* as a pioneer species because of its drought and salt tolerance, and association with N-fixing actinomycetes. Due to its high tannin content, however, decomposition of casuarina leaf litter is very slow. A local red-legged millipede (*Epibolus pulchripes*) was introduced into the young tree plantation and proved effective at steadily converting litter into rich organic soil (Haller and Baer 1994). These millipedes reach a length of 11 cm, are most active during the rainy season and enjoy protection from predators by a chemical defense that they can eject to a distance of 30 cm. Within 25 years, an organic soil horizon more than 10 cm thick developed that now supports a wide variety of other, more valuable plant species (World Bank 1996).

Conclusion

The role of soil biota and their accompanying biological, chemical and physical processes are important to soil health and ISFM. Soil health is not a production objective of small-scale farmers per se, but rather its attributes contribute to the productivity and sustainability of lands they manage. Soil health is, however, a societal goal because it is intimately associated with environmental protection. Promoting soil biodiversity and beneficial biological processes serve as tools within ISFM but ones that require developed understanding by practitioners. Soil biota are manageable by fostering their habitats and through direct introduction, although competitive barriers presented by indigenous soil organisms may limit the beneficial impacts from inoculation. Diagnostic tools are available for use in both the field and laboratory that assist in the management of soil biota and these tools should be nested into all ISFM development activities. To a large extend the success of deploying rock phosphate as a substitute for imported P-bearing fertilizers rests on the abilities of beneficial microorganisms to solubilize and assimilate these agro-minerals. Similarly, connecting smallholders' nitrogen and protein requirements to massive atmosphere reserves depends upon better management of nitrogen fixing organisms and symbioses.