Part III

The Process of Implementing ISFM

Chapter 11. Soil fertility diagnosis

Plants require different nutrients over a wide range of concentrations. Oxygen, hydrogen and carbon represent about 96% of plant dry matter and are supplied through the atmosphere and water. Some symbiotic plants also secure nitrogen from the atmosphere as well. Plants obtain the remaining nutrients through soil (Table 11.1). These elemental nutrients are divided on a practical basis into macronutrients (nitrogen, phosphorus and potassium), secondary nutrients (calcium, magnesium and sulfur) and micronutrients (zinc, iron, manganese, copper, boron, molybdenum and cobalt).

Table 11.1. The approximate concentrations of nutrient elements required for healthy plant growth (after Edwards 1971).

Element	concentration in dry matter (mg per kg)
Oxygen	480000
Carbon	420000
Hydrogen	60000
Nitrogen	14000
Potassium	10000
Calcium	5000
Magnesium	2000
Phosphorus	2000
Sulfur	1000
Chlorine	100
Iron	100
Manganese	50
Boron	20
Zinc	20
Copper	6
Molybdenum	0.1
Cobalt	trace
Silicon	trace
Sodium	

Understanding nutrient concentrations and their visual deficiency symptoms in plants is a very powerful diagnostic tool. Common deficiency symptoms such as tip burn, chlorosis and necrosis are characteristically associated with more than one mineral deficiency and also with other stresses not related to mineral nutrition. However, these symptoms are extremely useful in assessment of nutrient levels in soils. Farm managers and soil scientist need to appreciate that deficiency symptoms are quite complex because each nutrient serves different biological functions in plant growth and each may have an independent set of interactions with a wide range of expression. The expression of these symptoms may be acute or chronic depending on the growth stage of the plant. Acute deficiency symptoms occur when a nutrient is no longer available for a rapidly growing plant whereas, chronic ones result when there is continuous sub-optimal supply of a particular nutrient at an insufficient rate to meet the plants' growth requirement. To correct both conditions, interpretive diagnostic skills must be developed and employed.

Soil fertility status may be diagnosed using three additional approaches, field tests of the most limiting nutrient, soil analysis using chemical procedures suited for either the laboratory or portable field test kits and, to a lesser extent, reliance upon remote sensing, expert systems and crop simulation models. Ideally, findings are then interpreted based upon three considerations; the identification and hierarchy of limiting nutrients, the expected crop response to applying limiting nutrients, and the costs and expected economic returns resulting from management interventions. Based upon diagnostic results, preliminary recommendations are formulated and tested on numerous farms for comparison to current practices and, if they prove to be more profitable, they are then formalized into land management advice to the agricultural community (Smaling *et al.* 1997). This advice may be further adjusted for different levels of production in response to changes in soil conditions, fertilizer price and commodity value. For example, when this approach is validated or adjusted by district or county extension agents, then fine-tuned recommendations applicable to dozens to several hundred farms result. This information is then distributed in extension bulletins through local farming associations. This is an effective model for fertilizer outreach where sufficient resources are available and farming associations are in place to assist in extension activities.

Plant nutrients, their deficiency symptoms and amelioration

A rapid but subjective means of soil fertility diagnosis is through nutrient deficiency symptoms expressed by plants. These deficiency symptoms are closely related to the metabolic role of different nutrients and their physiological mobility within the plant. While these deficiency symptoms may vary between plants, general traits are usually expressed across most crops (Table 11.2). Interpretation of plant deficiency symptoms are both immediate and inexpensive. They are not based upon proscribed sampling or processing, rather diagnosis is based upon visual information and past experience. Plant nutrient deficiencies can have a profound impact upon crop productivity and land managers are well advised to acquire skills in their interpretation.

Basing one's soil fertility management decisions solely upon plant deficiency symptoms, however, has numerous drawbacks. Plant nutrient disorders are often confounded with other conditions such as moisture stress, waterlogging and plant pathogens. Insufficient soil moisture reduces the availability of nutrients and results in superficial deficiencies. The same is true of waterlogging, where anaerobic conditions cause nutrients to assume forms that are less available or even toxic to plants. This situation occurs with reduced nitrogen availability in saturated soils because the assimilation pathways of many plants require nitrate rather than ammonia or other reduced forms of nitrogen. In this way, the advantage of ready interpretation of characteristic plant deficiency symptoms also poses a hazard of misdiagnosis.

Table 11.2. Plant nutrients, their metabolic roles and common deficiency symptoms.

Nutrient	Principle metabolic roles	Plant deficiency symptoms
Nitrogen	amino acid synthesis	basal leaf chlorosis
Phosphorus	electron transport, nucleic acid synthesis	purpling of lower leaves, delayed flowering, reduced grain size, stunting
Potassium	osmotic regulation and transport of photosynthates	Marginal necrosis (tip burn), necrosis in the interveinal areas and interveinal chlorosis
Calcium	cell wall formation	apical leaf chlorosis
Magnesium	enzymatic activities including photosynthesis	light interveinal chlorosis, gray metallic sheen or dark freckles of leaves and necrotic areas along the veins
Sulfur	amino acid synthesis	generalized leaf chlorosis
Copper	catalyst in photosynthesis and respiration	curled leaves, petioles bent downward and light overall chlorosis
Iron	enzyme function and protein synthesis	strong chlorosis at the base of the leaves with some green netting
Zinc	synthesis and function of enzymes	interveinal chlorosis of new growth, rosetting of terminal leaves
Manganese	catalyst in photosynthesis and the synthesis and function of other enzymes	reduced growth and development with pale yellow younger leaves or necrotic spotting,
Molybdenum	needed for nitrate reduction and symbiotic nitrogen fixation	general chlorosis without the reddish coloration starting with lower leaves
Boron	assist in the metabolic function of plant and aids in cell division	poor stem and root growth, terminal necrosis or disfigured apices
Cobalt	ethylene and vitamin B12 synthesis and needed by rhizobia in legume root nodules	poor root nodulation by legumes and premature fruit drop

Even when plant nutrient deficiency symptoms are correctly identified, this information may be of little value. In some ways, by the time that visual symptoms are expressed, physiological damage has already occurred and it may be difficult to correct nutrient availability to the affected plants. Nitrogen and potassium are fortunate exceptions to this rule, however, because salts of these nutrients are readily soluble and mobile in soils. Nitrogen in particular is best delivered in a series of top-dressings rather than as a pre-plant application. Other nutrients, particularly phosphorus and micronutrients, are much less mobile. Sulfur, calcium and magnesium represent intermediate cases, depending upon their form. Correcting plant deficiencies for less mobile nutrients has several implications; top-dressing is ineffective and side drilling is less effective, incorporating nutrients into the soil between plants may cause further damage to the crop roots, and the more available forms of mineral nutrients tend to also be the most expensive. A brief description of plant nutrients, their deficiency symptoms and remediation based primarily upon Russell (1973) and Tucker (1999) follows.

Nitrogen (N). Nitrogen is among the three major nutrients essential for plant growth. It is a vital constituent of protein and protoplasm and therefore necessary for biomass increase and reproduction in plants. It occurs in all enzymes necessary for proper plant functions. Plants assimilate N as nitrate and ammonia and in some cases urea that enter roots by diffusion and mass flow and is readily translocated throughout the plant. The characteristic symptom of N deficiency is chlorosis of the lower leaves. A light red cast may also be seen on the veins and petioles. Under moderate N deficiency, the older mature leaves gradually change from their normal characteristic green appearance to a much paler green. Under extreme deficiency leaves become pale yellow, even white, and die. Major causes of N deficiency include insufficient soluble N in the soil solution, pH imbalance hindering nutrient absorption, excess leaching, waterlogging and plant competition for limited N reserves.

Nitrogen deficiency is readily corrected using a fertilizer containing ammonium, nitrate or urea depending on the physiology and growth stage of the crop, and soil climatic conditions. Nitrate is most readily available and mobile, ammonium and urea often require microbial transformation (oxidation) prior to plant assimilation. Nitrogen is least available under cool, dry conditions and most available in warm, moist soils. Other remedial measures include improved drainage of waterlogged fields, weeding to eliminate competition for nutrients and liming to adjust the pH. Intercropping or rotations including symbiotic N-fixing legumes offer direct advantages of N supply from the atmosphere and residual sources of organic N in crop residues, roots and nodules.

Phosphorus (P). Phosphorus is involved in plant energy relations and in the structure of nucleic acids and is available to plants in the form of hydrated ortho-phosphate in the soil solution. Purple or bronze leaves are common deficiency symptoms, appearing first on lower leaf tips and progressing along leaf margins until the entire leaf is discolored. Because P is mobile within plants, symptoms are first expressed on lower leaves. In many cases, early deficiency symptoms are not distinct and thus more difficult to identify but severe deficiency results in stunted growth and arrested physiological development. Soil pH greatly affects P availability to plants, becoming fairly insoluble at both low (<4) and high (>8) pH levels. In addition, phosphates are sorbed onto and within clay particles, especially oxides. Other factors that hinder phosphorus uptake by plants include lack of oxygen, insufficient soil moisture, extreme soil temperatures and the absence of symbiotic mycorrhizal fungi. Much of the total soil P is contained in soil organic matter and slowly mineralized through its decomposition. Phosphorus fertilizers are generally applied and incorporated before sowing as their mobility in soils is limited.

Potassium (K). Potassium is involved in osmotic regulation of cells in its ionic form regulating the turgor of non-woody plant organs and stomatal functions. Plants are able to readily extract the available K from soil through bulk flow and selective uptake and the nutrient is very mobile within plant tissue. Potassium deficiency symptoms first appear on older leaves as it is translocated from lower to older to younger plant tissues. Leaf deficiency symptoms are marginal chlorosis progressing into a dry leathery brown necrosis of mature leaves. Often interveinal necrosis progresses to the midrib with veins remaining green. In some cases, early deficiency is expressed as white speckling or freckling of the leaf blades and in others severely affected leaves will curl or crinkle. Unlike nitrogen, symptoms induced by K deficiency are irreversible. Conditions that reduce uptake of K by roots are poor moisture availability and low temperature. Potassium is retained on the cation exchange complex but may be displaced by more strongly charged cations, particularly calcium and magnesium, and subsequently lost to leaching. Potassium fertilizers can be obtained as single formulations such as potash or in blends and compounds with other nutrients. In some plants, such as cabbage, celery and turnips but not cereals or field legumes, the role of K can be partially replaced by sodium, but this should not be considered a remediation measure.

Calcium (Ca). Calcium is essential for plant growth, cell division and enlargement. Calcium is a component of cell membranes and is important for developing roots, shoot tips, storage organs and woody tissues. Calcium enters as a bivalent cation through the root via bulk flow and its entry and assimilation is impeded by excess soluble aluminum. The major causes of Ca deficiency are low soil pH, water shortage and excess magnesium. Within plants it is relatively immobile and deficiency symptoms first develop within growth tips or developing tissues. Classic symptoms of Ca deficiency include blossom-end rot of tomato, tip burn of lettuce and death of the growing regions in many plants. All these symptoms display soft dead necrotic tissue in rapidly growing tissues. Slower growing plants have a limited capacity to translocate Ca from older leaves, resulting in marginal chlorosis and downward cupping. Plants developed under marginal Ca deficiency are more prone to moisture stress while excess Ca leads to magnesium and boron deficiencies. Low Ca levels in the soil can be corrected by adding agricultural lime, which also raises soil pH, or as carrier materials of other fertilizers, such as super phosphate or calcium ammonium nitrate.

Magnesium (Mg). Magnesium is an ionic component of chlorophyll, the substance giving leaves their green color. Under Mg deficiency the older leaves turn yellow and interior portions may express red or brown pigmentation leading to leaf drop. Severe deficiencies result in stunted growth. In its advanced forms, Mg deficiency may superficially resemble K deficiency but its deficiency symptoms begin with mottled chlorotic areas developing in the interveinal tissue. The interveinal laminae tissue tends to expand proportionately more than the other leaf tissues, producing a raised puckered surface, with the top of the puckers progressively advancing from chlorotic to necrotic tissue. Deficiency is commonly present in sandy soils with low CEC, especially those derived from calcium carbonate, or in highly weathered acidic soils. Deficiency may also be induced by excess liming or application of K-bearing fertilizers. Mg deficiency is best avoided by incorporating dolomitic lime, balancing Ca and Mg inputs, and treated by applying dissolved magnesium sulfate.

Sulfur (S). Sulfur is a constituent of some amino acids and thus important in protein synthesis, and also a constituent of many plant oils. Uptake occurs in the form of sulfate from the soil solution. Deficiency symptoms on leaves loosely resemble the chlorosis found in nitrogen deficiency, but yellowing is more generalized over the entire plant, in part because of sulfur's reduced mobility. In some cases, the underside of the leaves becomes red and the petioles express a pinkish tone. With advanced S deficiency, brown lesions or necrotic spots may develop along the petiole, and the leaves become more erect or twisted and brittle. Excess S may result in defoliation. Sulfur lowers soil pH and deficiencies are more common in sandy soils low in organic matter. Deficiencies are avoided or treated by applying sulfate-bearing fertilizer, as these are readily dissolved and sulfate is quite mobile in soils. For example ammonium sulfate readily rectifies S deficiency in growing plants while providing a source of needed nitrogen top-dressing, but has only short-term effects upon S supply. Applying gypsum at rates of 50 to 100 kg ha^{-1} offer longer-term benefits, as does building soil organic matter.

Copper (Cu). Copper plays a role in nitrogen metabolism and osmotic regulation. Cu deficiency may be expressed as a light overall chlorosis along with the permanent loss of turgor in the young leaves. Recently matured leaves show netted green veining bleaching to a whitish gray. Some leaves develop sunken necrotic spots and have a tendency to bend downward. Trees under chronic Cu deficiency develop a rosette form of growth. Leaves are small and chlorotic with spotty necrosis. Deficiency appears first on maize within the whorl and on young expanding leaves as interveinal chlorosis. Leaves emerging from the whorl may remain tightly curled while leaf tips and margins die. Cu deficiencies symptoms occur mainly in sandy soils, with low organic matter. Use of copper sulfate mixed with water and applied as foliar spray at a rate of 100 to 200 g Cu ha^{-1} corrects its deficiency.

Iron (Fe). Iron forms a major component in many enzymes in the plant, including the production of chlorophyll and likely enters the root as both ferrous (Fe^{2+}) and ferric (Fe^{3+}) ions. Because Fe has a low mobility, its deficiency symptoms appear first on the youngest leaves. Deficiency symptoms commonly begin as interveinal chlorosis of the youngest leaves, leading to overall chlorosis and leaf bleaching with necrotic spots. Fe deficiency is strongly associated with calcareous soils and anaerobic conditions, and it is often induced by an excess of heavy metals in very acidic soils. Excess zinc and phosphorous also interfere with Fe availability. Up until the time the leaves become completely white, affected plants can recover from Fe deficiency through treatment with cheated foliar spray.

Zinc (Zn). Zinc is involved in protein synthesis and regulation of enzyme systems for energy production, and is available in the soil as a divalent cation. In the early stages of Zn deficiency, younger leaves become yellow and pitted in the interveinal upper surfaces of the mature leaves. As the deficiency a progress, intense interveinal necrosis occurs while the main leaf veins remain green. In many plants, especially trees, the leaves become very small and the internodes shorten, appearing rosette-like. Zn deficiency mainly occurs in sandy soils low in soil organic matter. Its uptake by plants is reduced by an increase in soil pH and the presence of high levels of phosphorus in soil. Applying blended fertilizers containing Zn fertilizer is an expedient way to avoid deficiency. Zn deficiency may be corrected by spraying zinc sulfate onto soil at a rate of 4 kg ha^{-1}.

Manganese (Mn). Manganese is involved in photosynthesis and protein synthesis. It is present in soils as divalent ions or insoluble oxides. Interveinal chlorosis is a characteristic deficiency symptom. In more severe cases, brown necrotic spots appear on leaves, resulting in defoliation. Cereal crops often exhibit some white grayish spots on their leaves. Many plants expressing Mn deficiency also suffer from inadequate P, masking its symptoms. Mn deficiencies may occur in saturated organic, acidic and sandy soils. Low soil pH interferes with Mn supply and can be corrected by liming. Manganese is best applied as micronutrient concentrates mixed with water and applied to the soil surface prior to tillage.

Molybdenum (Mo). Molybdenum is needed for nitrate reduction and BNF. It is taken up as monovalent or divalent molybdate (MoO_4^- or $HMoO_4^{2-}$) through bulk flow into plant roots. An early symptom for Mo deficiency is a general overall chlorosis, similar to the symptom for nitrogen deficiency but generally without the reddish coloration on the undersides of the leaves.

In many plants there is also upward cupping of the leaves and mottled spots developing into large interveinal chlorotic areas. Deficiency symptoms occur on acidic sandy soils and an increased soil pH enhances plant uptake. At high concentrations, Mo has a very distinctive toxicity symptom where leaves turn a very brilliant orange. Deficiencies may be corrected by applying sodium or ammonium molybdate at rates of 70 to 250 g ha^{-1}.

Boron (B). Boron contributes to cell wall formation, carbohydrate transport and pollen development. Boron deficiency symptoms first appear at the meristem resulting to stunted growth. Deficiencies are commonly found in acid, sandy soils in regions of high rainfall, and those with low soil organic matter. B deficiencies become prominent during drought periods when root activity is restricted. Applying borax (1.5 kg ha^{-1} B) or boric acid (200 g B ha^{-1}) can alleviate deficiency for several seasons. The tolerance of plants to B varies greatly, to the extent that the B concentrations necessary for the growth of plants having a high B requirement may be toxic to plants sensitive to B.

Cobalt (Co). Cobalt is associated with ethylene synthesis, permitting ripening of fruits, contained within vitamin B12 and is synthesized by rhizobia in legume root nodules. It occurs as a divalent cation in soils. Deficiency symptoms include poor nodulation by symbiotic legumes and premature dropping of fruit. Co availability is reduced by liming and increased by short-term waterlogging. Co deficiencies may be corrected by spraying only 25 to 125 g Co per ha as cobalt sulfate.

Other elements. Some other elements are assimilated by plants but may not play an essential physiological role within them, including sodium, silicon and chlorine. In some cases, the concentrations of these elements may be high within plant tissues because roots have no mechanism to exclude them. In others they may be involved in subtle metabolic processes that are not fully understood.

Diagnostic Approaches

Soil and plant testing occupy an important function in fertilizer targeting and recommendations, but their roles must be balanced with technical realities, analytical capacities and farmers' knowledge of soil fertility and crop nutrition. Soil testing may be employed in near-term planning and has both empirical and analytical aspects. Farmers may identify limiting nutrients by establishing fertilizer test strips or by collecting soil samples and analyzing them for their available nutrient contents. The former is more time consuming, and the latter is more expensive. Chemical analyses may be conducted using simple colorimetric test kits or by submitting soil samples to a laboratory for nutrient extraction and measurement. In either case, it is important that recommended actions drawn from the analytical results be calibrated to crop performance and economic return.

Field test strips. Farmers may establish test strips of different mineral fertilizers within their fields as a means of assessing which nutrients are limiting crop growth and which fertilizers best correct this condition. The technique is simple, small amounts of different fertilizers are incorporated into the soil, their placement is marked for later identification, the field is planted and the effects of fertilization noted later in the season (Figure 11.1). When N, P and K-bearing fertilizers are applied side-by-side, farmers can determine which micronutrient is least available in their soil. This exercise can also raise farmers' knowledge of plant deficiency symptoms and corresponding fertilizer management. It requires, however, that: 1) the correct fertilizers are available in small quantities because small-scale farmers are unlikely to purchase several different 50 kg bags simply to test them, and that these fertilizers are applied at sensible rates, 2) the test strips are installed in a way that the fertilizer effects are clear and not confounded, 3) farmers have access to extension advice and illustrations that describe resulting nutrient deficiency symptoms and 4) farmers recognize that more than one fertilizer may be necessary because ameliorating the most limiting nutrient often results in expression by another. In other words, a hierarchy of limiting nutrients exists as described by Liebig's Law of the Minimum (Russell 1973) and correcting the most severe limitation often induces the next one. A straightforward means of stimulating use of field test strips is to assemble fertilizer kits accompanied by instructions and diagnostic illustrations. These kits may be distributed through farmer organizations to facilitate peer support, sold through retail networks, and possibly subsidized by fertilizer distributors in order to stimulate demand. Improved local recommendations may also be formulated when the results from several test strips are compiled and interpreted.

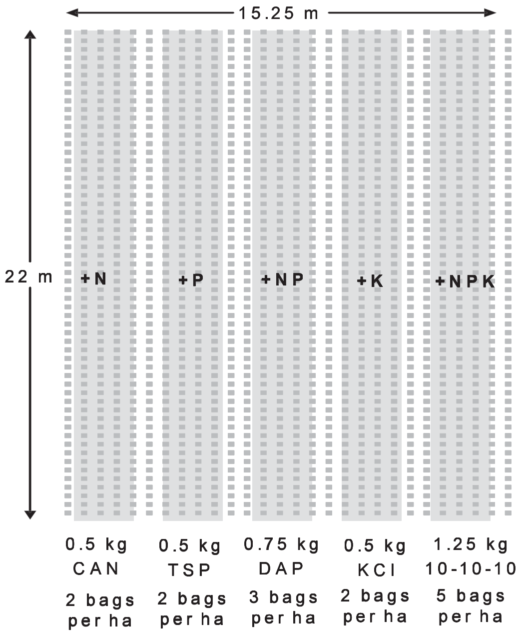

Figure 11.1. An example of fertilizer test strips installed at a moderate fertility level intended for on-farm diagnosis of fertilizer requirements. Each strip is equivalent to 0.005 ha containing 300 maize plants in four 75 cm rows.

Fertilizer recommendations intended for use by commercial farmers in developed countries are generated through the analysis of repeated, multiple location field experiments. These experiments compare the responses of important crops to the type and rate of plant nutrients applied. The selection of sites investigating fertilizer responses must be representative of the range of agro-ecologies and soils. Researchers usually rely upon factorial treatment arrangements of plant nutrients such as N, P and K singly, and in combination at different rates (0, 25, 50, 75, 100 kg ha^{-1}), resulting in rather large experiments. Because of their complexity and size, these experiments are usually conducted within research stations or larger commercial farms where all other conditions that constrain yield such as moisture stress and pests can be controlled. The investigation sites and surrounding areas must be carefully characterized to assist in the extrapolation of findings.

Soil sampling. Whether or not soils are to be analyzed by portable colorimetric test kits or in laboratories, it is important that representative soil samples be recovered, processed and labeled before analysis. It is not necessary that farmers randomize their sampling positions, but they must understand that several samples should be collected across the field, bulked, mixed and a representative composite sample recovered. Greater variation in soil properties results from fewer sub-samples Houba *et al.* (1990) demonstrated that a Coefficient of Variation (C.V.) of 40% resulting from five cores is reduced to 20% when 20 to 30 cores are collected. Okalebo *et al.* (2002) recommend that nine to twelve soil cores be collected to uniform depth of 15 to 20 cm in a zigzag or diagonal pattern across a field no larger than 0.4 ha (one acre), bulked and then analyzed in duplicate. Sample preparation using portable soil test kits is particularly tedious because of the small quantity of soil used in the colorimetric reactions and the lack of opportunity to dry and finely sieve the samples.

Soil test kits. Soil test kits are virtually unknown in Africa but may offer opportunity to better target fertilizers. They permit land managers to quickly and inexpensively test soil nutrients in the

Table 11.3. Soil test kits offered by La Motte in the USA, their price and the cost per analysis.

Product	Analyses performed	Price	Cost per analysis
Garden Soil Test Kit	30 pH, 15 N, 20 P, 15 K	\$55, reagent refill \$52	\$0.69, \$0.65 w/refill
Deluxe Test Kit	60 pH, 30 N, 40 P, 30 K	\$93, reagent refill \$73	\$0.58, \$0.46 w/refill
Organic Matter Kit	25 tests (requiring 5 reagents)	\$329, reagent refill \$115	\$13.16, \$4.60 w/refill
Macronutrient Plant Tissue Test Kit	50 N, 50 P, 50 K (provides qualitative results only)	\$93, reagent refill \$83	\$0.62, \$0.55 w/refill
Professional Soil Test Kit	100 pH, 50 each N, P, K, Mg, Mn, Al, Fe, Cl, nitrate, nitrite, ammonium, humus	\$434, reagent refill \$262	\$0.62, \$0.37 w/refill

field. These kits typically rely upon filtered extraction followed by colored reactions, and then the results are read from a color chart. Many such kits intended for use by gardeners and farmers are available in garden shops and farm supply outlets in developed countries. The scope of these kits is well represented by the product range of LaMotte, consisting of garden, specialized and professional test kits (Table 11.3). The professional test kit in Table 11.3 is literally a laboratory in a suitcase that opens to reveal reagent shelves, test tube and filtration racks and procedural and interpretive literature. These professional kits may in fact be too sophisticated for the purpose of fertilizer targeting in Africa because a strong working knowledge of chemistry is required, suggesting that the less expensive Garden Soil Test Kits would be sufficient for most purposes.

Soil test kits provide crude quantitative results that, with some experience, can be translated into fertilizer rates. Some kits present their results in parts per million and others in pounds per acre. These results are assumed interchangeable because an acre of topsoil weighs about one million pounds. Pounds per acre and kilograms per ha are considered roughly interchangeable (1 kg = 2.2 pounds and 1 ha = 2.5 acres). Thus, if a soil test reveals 20 mg kg^{-1} and a crop requires 50 kg ha^{-1}, then 30 kg ha^{-1} of that nutrient are required as mineral fertilizer. Test kits are accurate, but not precise because they are scaled in large increments. Very small amounts of soil are measured so representativeness of the samples is an issue. In some cases, smaller test kits may be better because they must be used before their reagents expire. Some oxidic tropical soils are likely to interfere with color development in the extracts. Nonetheless, perhaps farmers and development specialists in Africa should be given the same opportunity as hobbyists in developed countries to determine how such kits may be used to better adjust their fertilizer practices.

Laboratory analysis. Quantitative analysis of plants and soils in a reliable, widely applicable and cost effective manner is of great importance to agricultural and environmental sciences, but less so to smallholder problem solving. Key developments in African agriculture rely heavily upon laboratory analyses including the characterization of soil nutrient cycling and depletion (Smaling *et al.* 1997), integrating the use of mineral fertilizers and organic matter (Janssen 1993), mitigating carbon loss and greenhouse gas emissions (Bouwman 1990), rehabilitating degraded lands and selecting crops for nutrient use efficiency and stress tolerance (DeVries and Toenniessen 2001). Chemical analysis services are offered by African national research organizations, universities and, to a lesser extent private companies. While the principles underlying various chemical determinations in African and developed countries are fundamentally the same, African laboratories generally lack expensive automated equipment and focus upon more labor intensive methodologies that require fewer reagents and consumables. These analyses and their appropriate methods recommended by Okalebo *et al.* (2002) appear in Table 11.4. Note that the procedures are either several decades old or are shortcuts from earlier methods. In general, soils are either extracted or digested, chemically reacted and then differences determined using titration or spectrometers. The only exception is the use of atomic adsorption spectrophotometers in the determination of Mg, Ca and micronutrients. One very simple method is not presented in Table

Table 11.4. Chemical analyses and procedures routinely practiced in African laboratories (after Okalebo *et al.* 2002)[1].

Analysis	General procedure
Organic C	Heated acid digestion and titration or colorimetric determination (Nelson and Sommers 1975)
Total N	Kjeldahl digestion and colorimetric determination (see Anderson and Ingram, 1989)
Ammonium and nitrate	Extraction, distillation and colorimetric determination (Bremner and Keeney 1965)
Extractable P	Olsen or Bray 2 extraction and colorimetric determination (Olsen et al. 1954, Bray and Kurtz 1945)
Exchangeable K, Mg and Ca	Ammonium acetate extraction followed by flame photometry for K and atomic adsorption spectrophometry for Mg and Ca (Cottenie 1980)
Exchangeable acidity	KCl extraction and titration to neutrality with sodium hydroxide (see "shortcut" by Anderson and Ingram 1993)
Soil extractable sulfate	Extraction with potassium phosphate followed by UV spectrophometry for turbidity (Fox, 1974)
Soluble Cu, Zn, Fe and Mn	Chelation with EDTA followed by AA spectrophotometry (Adams 1965)

[1] for references to individual analyses see Okalebo et al. 2002; and Bremmer and Keeney, 1965

11.4, separation of organic matter and ash by combustion at 550°C for eight hours in a muffle furnace. This procedure is useful in comparing the quality of different composts and manures.

A useful example of an operating soils analytical laboratory is that of the Kenya Agricultural Research Institute at Muguga. The laboratory was started in 1952 and conducts its plant and soil analyses as a public service at cost recovery. Plant analyses include not only mineral nutrient contents but also parameters related to feed value. Soil analyses include both soil physical properties and nutrient contents. Some of the fees charged for analysis are presented in Table 11.5. In 2006 the laboratory analyzed 4016 samples (about 15 per day). The service is mostly used by other researchers, including university students, and large commercial farms, but some NGOs submit farmers' samples as well. The quantitative results from samples submitted by researchers are relayed to clients as is, but those from farmers or development agencies are further interpreted. Results are then sent by post. The cost of soil preparation and N-P-K analysis is $12.65 (Table 11.5), sufficient funds for a small-scale farmer to purchase about 20 kg of fertilizer (see Table 2.2).

Australia represents a useful example of how laboratory testing is translated into fertilizer recommendations for tropical soils (Box 11.1). As many as 18 different analyses are considered in framing fertilizer advice (Peverill *et al.* 1999). Soil analyses may then be translated into recommendations using two contrasting approaches based upon either the sufficiency or the build-up and maintenance concepts (Olsen 1987). Sufficiency establishes production targets and calculates the nutrient additions required to meet them. Build-up and maintenance first establishes critical soil test values required to meet crop demands (build-up) and then replaces nutrients as they are lost over time (maintenance). Sufficiency tends to generate lower recommendations that may be adjusted by other interpretation factors (Box 1.1) and are best applied to soils that are moderately infertile. Build-up and maintenance is applied to the least fertile, shallow or sandy soils, often requires massive initial fertilizer additions and is similar to the nutrient replenishment concept advocated by Buresh *et al.* (1997) to meet soil nutrient depletion in Africa. The sufficiency concept seems most consistent with the principles of ISFM and, if properly applied can also satisfy the nutrient requirements in the least fertile soils. Overall, the Australian experience in soil testing and fertilizer advice sets a very high standard that relies upon detailed soil analyses and adjusts recommendations to individual farm conditions (Peverill *et al.* 1999). This system is intended for large-scale commercial farmers and ranchers use, and a mechanism offering similar services to African small-scale farmers would likely assume a very different form.

Economic realities prevent small-scale farmers from taking advantage of laboratory soil analysis. Although all laboratories will analyze soils for a fee, these laboratories are few while smallholders are many, often remote and cannot be expected to travel twice simply to submit a soil sample and later collect its results. Moreover, smallholders' lands are often heterogeneous and to sample across large differences confounds results, requiring that many samples be collected and analyzed. The fees for soil analysis are often prohibitive and ironically, for many smallholders the cost of soil analysis may be greater than the cost of ameliorative actions in the field. Also, even when soil analyses are conducted with accuracy and precision, their results are often ambiguous and cryptic to most African farmers. We suggest that field test diagnosis of fertilizer needs by farmers, assisted by experienced neighbors and front-line extension agents, is more practical than reliance upon soil tests and that soil analysis should be performed only when anomalous field conditions are encountered

Box 11.1. Non-test factors used to adjust fertilizer advice in Australia (after Heyar and Price 1999)

Fertilizer guidelines resulting from soil tests may be adjusted by other factors that account for:

1. nutrient supply from beyond the soil sample
2. nutrients recycled from organic sources
3. nutrients resulting from deposition, weathering, nitrogen fixation and contaminants in mineral fertilizers
4. difference is nutrient use efficiency by different crops and for different nutrients

These adjustments require detailed understanding of the soil profile, biogeochemical cycles and nutrient uptake similar to considerations employed within ISFM.

Several issues are raised when considering the current status of soil and plant testing in Africa. Where farmers have few fertilizers available to them, care must be taken that those which are imported and distributed contain significant amounts of the nutrient(s) that are limiting within the major agricultural soils. In areas where several different fertilizers are available, guidelines must be developed to assure that farmers understand which are needed for their conditions and in which amounts. The field fertilizer test strips used by researchers should become commercialized, perhaps through collaboration between national scientists and local fertilizer distributors. Now is the time to introduce and manufacture soil test kits to Africa as a means to fine-tune fertilizer recommendations. If every mid-level extension agent, NGO and farmer association made use of these kits, stronger farmer knowledge of soil fertility management is sure to follow. The costs of these kits could be reduced by more local packaging of the refill kits, as these consist of fairly simple reagents. Again, national scientists working with agro-dealers and the manufacturers of test kits could fill this void.

The role of modeling. Several crop simulations models are available that, once mastered, initialized and validated, can serve as useful tools in evaluating candidate soil fertility management recommendations. Some crop simulation models, such as the DSSAT family of crop models (Jones *et al.* 2002) are intended for use in comparing different management practices. Others that were constructed to simulate carbon and nutrient dynamics, such as the Century Model (Parton *et al.* 1994, Metherell *et al.* 1993) have had crop modules added to them. Yet other models, such as NUANCES (Rufino *et al.* 2007) simulate not only nutrient dynamics and crop yield, but also include

Table 11.5. Cost recovery fees charged per sample for soil and plant analysis by KARI in Kenya.

Analysis	Cost ($)
soil preparation	0.86
organic carbon	4.29
total N	4.29
extractable P	3.93
exchangeable bases (ea)	3.57
micronutrients (ea)	1.43
plant preparation	1.07
total N	4.29
total P	4.29
acid detergent fiber	7.14

economic analyses within their outputs. One difficulty with widespread use of simulation models is the large amount of soil, climate and crop information required to initialize and validate them compared to the cost and time required to conduct more straightforward agronomic field tests.

In many cases, the resources used to collect this information could be redirected toward more empirical problem-solving drawing more immediate benefits. However, when models are initialized and validated with broadly applicable data, as with the main crop grown on a major soil type in a large AEZ, then the models can be used in a predictive capacity to screen through a large number of management changes in order to develop a shortlist for field testing. A problem with applying simulation models is that their sub-routines for N and P may be strong, but those for nutrient bases, S and micronutrients are weak or absent.

Integrating diagnostic approaches

Field experiments are required to verify nutrient deficiencies identified from soil analysis or recognition of visual symptoms of deficiencies in crops. Experiments are also required to reliably establish how much input is required to achieve a given yield, which is important for economic analysis. Soil testing alone is not sufficient and field experiments on major crops are required to calibrate soil tests, verify nutrient deficiencies, establish yield responses to fertilizer, and identify risk factors for poor response to fertilizers. Soil and plant testing programs used in conjunction with field experimentation have been an essential component of agricultural development strategy for many decades in developed countries to assess the nutrient status of soils and to formulate fertilizer recommendations that maximize the efficiency use of fertilizer (Saver and Campbell 2001). Small plot trials conventionally used by researchers can be simplified for use by farmers in the form of fertilizer test strips. This is a key tool for fine-tuning recommendations to individual fields. It is more time consuming than soil testing but much less expensive. Packs of seed, fertilizer and instructions for test strips could become commercialized for use by farmers, perhaps through collaboration between national scientists and local fertilizer distributors.

Risk factors for poor crop response need to be identified, so that farmers can avoid them if possible. Some of these are well known and easy to recognize such as late weeding, while others involving soil deterioration are more subtle. In particular, critical levels of soil organic carbon, below which there is no response to mineral fertilizer, need to be established and soils monitored in relation to this threshold. Responses to organic amendments and their role in increasing use efficiency of mineral fertilizers must be quantified to establish guidelines on efficient use of both resources. Furthermore, field experiments must be conducted for more than one growing season and at a sufficiently large number of sites to cover the soils and climatic conditions in the area for which generalizations are intended.

A major shortcoming in diagnostic capacity within Africa is the paucity of reliable, inexpensive soil test kits. Practical soil test kits suitable for Africa's highly weathered soil must be designed, field tested and commercialized, and training and incentives provided for their application to soil fertility diagnosis. The precision of these tests are relatively crude but are sufficient to derive advice concerning the types and amounts of fertilizer required to meet yield targets. Simply importing test kits from elsewhere may not prove useful because some colorimetric tests developed for temperate soils cannot perform in heavy, oxide clays. Local production of reagent refills would reduce the costs of operating test kits by streamlining transportation and importation costs.

Soil and plant testing occupy an important function in improved targeting and recommendation but their roles must be balanced with technical realities, analytical capacities and farmers' knowledge of soil fertility and crop nutrition. Soil testing may be employed in near-term planning and has both empirical and analytical aspects. Chemical analyses may be conducted using simple colorimetric test kits or by submitting soil samples to a laboratory for nutrient extraction and measurement. In either case, it is important that recommended action be drawn from the analytical results and calibrated to field experience.

Chapter 12. Soil fertility management advice

Need exists to move away from blanket fertilizer recommendations to basing guidelines upon the principles of ISFM, thus offering farmers the opportunity to make more judicious and synergistic use of available organic resources and purchased inputs. Most blanket fertilizer recommendations were formulated many years ago and disregard the potential benefits from organic resources, variations in soil properties and climate, and the changing relationships between production costs and commodity prices. As a result, several existing recommendations may be considered obsolete. In many cases, fertilizer labels only report the contents of macronutrients, ignoring the secondary and micronutrients. Past fertilizer recommendations focus on the maximum yield attainable for broad agro-ecological regions, whereas individual farms may be extremely heterogeneous. To account for these shortcoming, it is important that recommendations be considered an informed starting point for further refinement by land empowered managers.

To a large extent, the formulation of fertilizer recommendations in Africa was adopted from approaches employed by more developed nations. Commercial farmers seek to optimize returns upon an area of land, and stand prepared to invest not only in nutrient supply but in additional inputs that overcome other constraints to production. This was also the model used during the Green Revolution (Okigbo 1990). This capacity greatly reduces risk of crop failure and enhances farmers' return to fertilizer investments in a manner consistent with established agronomic and economic principles. This approach is not necessarily relevant to small-scale farmers because they operate within a radically different investment environment.

Smallholders seek to maximize returns per unit input because they are unable to purchase sufficient fertilizer, and other inputs, at the recommended levels designed to optimize crop production. Often to compensate for shortfalls in farm inputs, they substitute labor for cash by collecting, processing and applying available organic resources. Furthermore, the risk of crop failure from drought, pests and disease is greater and must be factored into their decision-making. These considerations are also sound and, as a result, the fertilizer recommendations appropriate to larger-scale commercial farming are considerably greater than sensible additions by small-scale farmers. This difference is seldom factored into fertilizer recommendations advanced to farmers by agricultural extension officers. Incidentally, the same findings used to calculate recommendations to commercial farmers using the point of diminishing returns also indicate where the response surface is steepest, suggesting that re-examination of existing data can generate improved recommendations. As described in Chapter 2, fertilizer recommendations adjusted to smallholders making efficient use of organic resources tend to be 30% to 50% of those formulated for commercial farmers (see Figure 2.3).

Examples from Africa

KARI (1994) cites that earliest fertilizer recommendations in Kenya were based upon 979 fertilizer trials conducted before 1985. These trials were mostly undertaken independendly and without detailed site characterization by agricultural scientists from farming backgrounds with strong intuitive skills. This approach was sensible, but not comprehensive. Starting in 1986, KARI conducted repeated fertilizer response trials at 71 well characterized and systematically selected sites (MoA-NAL 1988) in order to generate fertilizer use recommendations published at the district level (KARI 1994). Recommendations within districts differed for long and short rains growing season, for various crops, intercrops and rotations. Crop response to fertilizer was compared to applied cattle manure but not to other organic resource managements.

During this period, the fertilizer industry experienced change as well. Fertilizer import quotas were abolished, subsidies withdrawn and the market was liberalized. At first, the importation and supply of fertilizers was reduced, but entrepreneurs moved into the market at all levels and, within a few years several types of fertilizer were available from local stockists throughout the country (Mwaura and Woomer 1999). Between 1990 and 2001 fertilizer consumption increased in Kenya by 43% to an average 29 kg ha^{-1}, which is 3.7 times that of sub-Saharan Africa as a whole. Indeed, this Kenyan example contains many important lessons but it does not represent a complete model for others to follow.

A danger exists when fertilizer recommendations are developed and disseminated in strictly top-down manner because feedback from intended beneficiaries is limited. This situation is especially true when recommendations are intended for farmers across a range of agro-ecological and socio-economic conditions. Basically, the technique employed by Kenya Agricultural Research Institute, Fertilizer Use Recommendation Project (KARI-FURP) in assessing fertilizer potential is valid, but the process did not involve farmers from its earliest stages and, in too many cases the recommended rates of fertilizer were well beyond the investment capacity of most smallholder clients. Even the levels of livestock manure (5 to 10 t ha^{-1}) that served as a comparison of organic resource management was unrealistically high. More realistic levels of organic inputs were later included within an innovative extension booklet published by KARI (Kinyanjui *et al.* 2000). This booklet assigned equal weight to mineral fertilizers and organic manures but, rather than making concrete recommendations, it presented a range of management choices available to farmers. The booklet was written in English but technically complex practices were accompanied by many useful illustrations. This booklet offered early insights into what was later termed ISFM but its inability to prioritize management options and assign them to particular farming systems and geographic areas was a shortcoming. Labor requirements and economic analyses of the different management practices were also not included. Extension agents, rural development specialists and farmer organizations throughout sub-Saharan Africa desperately need similar booklets that also include economic analyses of targeted land management interventions (Patel *et al.* 2004).

There are both positive and negative examples on soil management and fertilizer recommendations from Malawi and Zimbabwe. Farmers in different geographical areas of Malawi receive area-specific soil fertility management recommendations. During the later 1990s, these fertilizer recommendations were captured into starter packs that were distributed to every farming household in the country. This approach not only resulted in bumper maize harvests but raised farmers' knowledge of mineral fertilizers (Blackie and Mann 2005). These sorts of initiatives increased Malawian fertilizer consumption to 39 kg ha^{-1} and led to effective distribution through retailer networks and farmer organizations. We note however that Malawi is a world leader in tobacco production and much of its fertilizer use is directed toward that cash crop (Denning *et al.* 2009). Malawi serves as a positive example in terms of managing fertilizer supply and consumption compared to its neighbors Tanzania, Mozambique and Zambia where fertilizer consumption stands at only 2, 5 and 8 kg ha^{-1}, respectively.

Zimbabwe has a relatively sophisticated fertilizer industry. The country processes rock phosphate, limestone and sulphide deposits into fertilizers (van Straaten 2002). It manufactures N fertilizer from hydroelectric power. Different compound fertilizers are produced, transported by train and marketed to farmers through retail networks. Data from FAO-STAT 2004 reported fertilizer consumption of 43 kg ha^{-1}, the highest in sub-Saharan Africa (excluding South Africa). Zimbabwe is currently experiencing massive changes in land tenure that affect its largest commercial farms and it will be interesting to note how land redistribution affects its fertilizer consumption in the future.

At the continental level, much attention has been focused on the quantification of nutrients entering and leaving agricultural systems, the balance indicative of the level of soil fertility depletion. Soil nutrient balance models also quantify the flows of nutrient inputs and outputs at micro-, meso- and macro-levels (Stoorvogel *et al.* 1993). Investment in soil fertility has now become a central feature of any program to improve agricultural productivity. The studies at continental and meso-levels are useful for policy-makers and help in the advocacy against nutrient depletion. Information derived from nutrient monitoring at farm level is more useful to farmers. The information can be used to either target fertilizer amounts on specific field plots or to direct overall fertilizer purchases for the farm. In general terms, nutrient monitoring computations assist in providing information used for designing good farming practices. Despite this advantage, detailed nutrient monitoring at farm level is time- and labor-consuming. Furthermore, such balances will tend to vary from farm to farm, compromising their extrapolation.

The other constraints to deriving more localized soil management recommendations include lack of appropriate soil maps and accurate data bases. For example there is only one global soil map at a scale of 1:5 million that was produced between 1971-1981 (FAO and UNESCO 1995). These maps show the distribution of soil types and their dominance and have not been widely used in SSA. These maps were subsequently digitized and only few parts of SSA are now covered by the Soil and Terrain digital database (SOTER), and the quality of that information is limited to soil classes. For example a polygon labeled Kikuyu red loam (a soil in Kenya) tells nothing about how much nitrogen it can supply to a maize crop (Sombroek *et al.* 1982). There is lack of consistency in data for different regions and scales and historic fertilizer use databases tend to be more available than those recommending specific soil managements.

In some cases, initial fertilizer recommendations have persisted for decades, but does this amount to agricultural negligence? In the past, only the largest farms were able to afford and access fertilizers through special arrangement. In most cases, fertilizers containing the recommended nutrients were not even available to small-scale farmers through existing market networks. Fertilizers arrived packaged in large bags (e.g. 50 kg) and it was often illegal to repackage them into smaller sizes without approved labels. Opportunity now exists to better target recommendations to specific biophysical and socioeconomic environments. Such a recommendation regime includes different advice based upon the market orientation and access of farmers in different AEZs. Thus, targeted recommendations can maintain sustainable production in the best-managed fields, enhance and sustain productivity of moderately responsive fields and restore and rehabilitate degraded soils. In general, these options involve judicious management of mineral fertilizers and farmer-available organic resources. Farmers are aware of the maximum yields they can obtain in different fields, which they generally categorize as good, medium and poor lands. This local knowledge can be factored into the amounts of inputs to be used in each field type. Fields that farmers know are poorly-responsive are candidates for land rehabilitation through fallowing or the application of organic inputs. A wider range of nutrients other than N, P, and K may be necessary in these degraded lands, including Ca, Mg and S, to provide better balanced nutrient supply. Targeting soil fertility input recommendations using ISFM principles results in greater fertilizer use efficiency that permits farmers to better recognize the benefits from smaller applications of mineral nutrients. This recognition will further encourages farmers to increase fertilizer use by applying them at progressively higher rates and to more marginally productive lands. An increase in farm profits plays an important role influencing the decision to use more fertilizers. Farmers' knowledge of fertilizers and their access to them must also be improved. New crop varieties that are more responsive to external inputs, and more tolerant of other biotic and abiotic stress must be commercialized and promoted as well. Re-examination of fertilizer use within the context of ISFM leading to more site-specific and flexible recommendations that are adaptable to small-scale farmers' biophysical and socio-economic conditions is a critical starting point for improving food security and rural livelihoods in SSA.

Fertilizer rates and blends

Fertilizer recommendations can vary widely depending upon underlying assumptions and farmer setting as illustrated by the advice for maize-bean intercropping in west Kenya forwarded by different organizations (Table 12.1). The Ministry of Agriculture Fertilizer Extension Project recommends rather high levels of DAP and CAN to commercial farmers seeking to optimize

Table 12.1. Examples of different fertilizer targets using DAP and CAN for maize-bean intercropping in west Kenya

Input regime	nutrient inputs (kg ha^{-1})	applied as (50 kg bags)	Cost ($ per ha)	Source
Very high	120 N, 40 P_2O_5	4 DAP, 3 CAN	173	MoA FEP
High	75 N, 20 P_2O_5	2 DAP, 2 CAN	100	KARI FURP
Moderate	35 N, 10 P_2O_5	1 DAP, 2 CAN	72	Best Bet
Low	21 N, 10 P_2O_5	1 DAP, 1 CAN	49	We RATE

yields of long duration maize in prime agricultural lands. KARI (1994) takes a similar approach but adjusts for the grain price-fertilizer cost ratio and risk of drought. Moderate recommendations resulted from the Best Bet Project (Woomer 2007) that was working with small-scale maize farmers moving from subsistence to market agriculture. Best Bet further advised that two tons of manure or compost may be substituted for the application of pre-plant DAP and that low cost urea may be substituted for CAN if it is quickly incorporated into the soil. This level of fertilizer inputs is similar to the nutrient target of 50 kg ha^{-1} established by the Africa Fertilizer Summit (2006). The Western Regional Alliance for Technology Evaluation (WeRATE) advanced an even lower recommendation for poorer farmers who were combating striga in West Kenya (AATF 2006). The relatively low rate was intended to assure that suppression of the plant parasite resulted in increased yield and recognizes the limited capacity for poor farmers to invest in larger amounts of fertilizer when they are also expected to purchase tolerant crop varieties and herbicides required to fight parasitic weeds.

Fertilizer recommendations have been most effective for major cash crops such as tea, coffee and sugar which are grown for well organized markets and for hybrid maize, which responds particularly well to chemical fertilizer. However, even this advice is often out of date due to changes in soil and economic conditions. Fertilizer is too seldom applied to traditional food crops such as millet and sorghum (Bationo and Mokwunye 1987). In order to achieve transport cost-effectiveness, most countries import fertilizer with high nutrient contents such as diammonium phosphate (DAP), urea, triple superphosphate (TSP), potassium chloride (KCl), and complex NPK fertilizers (IFDC 1996). Most of these fertilizers contain fewer secondary nutrients such as S, Ca and Mg and these deficiencies are becoming more common.

The use of high-yielding cereal varieties along with the increasing use of fertilizers containing major nutrients, even without micronutrients or organic inputs, can dramatically increase food production under many intensified systems (Okalebo *et al.* 2003). However, as a result of depletion of other nutrient reserves in the soil, this practice can also lead to nutrient disorders and imbalances (Levin *et al.* 1993; Bouis *et al.* 1999). Micronutrients are required by plants in small quantities, but they limit plant growth and substantially lower yields when deficient. In SSA, only a few studies (Schutte 1954; Sillanpaa 1982; Kang and Osiname 1985) have documented the micronutrient status of soils, as compared to the enormous amount of literature available on macronutrients. The study by Sillanpaa (1982) showed that copper, zinc and molybdenum deficiencies are common in many coarse textured, acid soils of Ethiopia, Ghana, Malawi, Nigeria, Sierra Leone, Tanzania, and Zambia. In other SSA countries, replenishment of micronutrients through fertilizers or other amendments has not yet been addressed.

Additions of micronutrients can improve the yield response to macronutrients on deficient soils. Nutrients such as Zn, B, S, and Mg may be included relatively cheaply in existing fertilizer blends. When targeted to deficient soils, these nutrients can dramatically improve fertilizer-use efficiency and crop profitability. Over the past 40 years, S, Mg, and less commonly Zn and B deficiencies were detected for maize on sandy soils in Zimbabwe (Grant 1981, Metelerkamp 1988). Enhanced yields were obtained by including selected nutrients in fertilizer blends (Grant 1981). Recent experience in Malawi provides a striking example of how N fertilizer efficiency for maize can be raised by providing appropriate micronutrients on a location-specific basis. Supplementation by S, Zn, B, and K increased maize yields by 40% over the standard N-P recommendation alone (Wendt *et al.* 1994).

In recognition of the need for balanced plant nutrition, diverse cropping systems and the heterogeneity in the African soils, various initiatives have been put in place for blending of fertilizers targeting different crops, soil type and AEZs. Fertilizer manufacturing and blending is shifting to ensure that fertilizers not only have the major macronutrients but also the secondary and micronutrients. In Kenya for example, the Athi River Mining Company has establish a facility capable of producing two new blends of fertilizer, a basal dressing and a top-dressing marketed under the brand name *Mavuno*. These fertilizer blends combine imported macronutrients N and P with locally granulated minerals of gypsum and dolomitic limestone, muriate of potash, and micronutrients B, Zn, Mn, Mo and Cu. Due to their secondary and micronutrient content, the *Mavuno* blends may outperform existing fertilizers, particularly where K and S become limiting and also where acidification of soils is increasing. In addition, the use of local minerals makes *Mavuno* blends less expensive than other fertilizers (Poulton *et al.* 2006).

Perceptions of management recommendations

Large differences exist between how fertilizer advice is perceived. Too often, agriculturalists formulating fertilizer recommendations regard them as approximations of an ideal, and as additional information is collected, that ideal is better approached. Empowered land managers understand that this is not the case, rather fertilizer recommendations represent an informed starting point that is adjusted to meet their changing site-specific conditions. The capacity for iterative improvement by land managers is not fully acknowledged and this has led to the continuation of over-generalized blanket recommendations advanced by many extension systems. The role of detailed fertilizer response studies must not be dismissed, but at some point attempts to continuously fine-tune fertilizer recommendations becomes a more time consuming, expensive and perhaps unnecessary alternative to the facilitation of more holistic on-farm problem solving by knowledgeable land managers. One of the advantages to ISFM is that it strikes a sensible balance between structured enquiry and iterative problem solving and advice emanating from it is both robust and flexible.

On the other hand, one can question the usefulness of fertilizer recommendations no matter how formulated, conveyed and interpreted, if they remain largely ignored. What difference is 100 or 400 kg ha^{-1} in a continent where average applications are only 8 kg? What is more, few farmers actually apply only 8 kg of fertilizer per ha, rather one farmer in five is applying 40 kg, or one farmer in ten is applying 80 kg, while the vast majority of smallholders have little or no experience with mineral fertilizers. The importance of farmer knowledge concerning fertilizers and soil health, and how this new knowledge is to be conveyed through training, agricultural extension and fertilizer marketing therefore assume critical importance. Again, ISFM offers a key perspective in developing and demonstrating this knowledge because of its balanced understanding of mineral fertilizers and organic resources. Depending upon their composition, amount and placement, organic resources may substitute for, accentuate, prolong, delay or counteract the effects of mineral fertilizers. Furthermore, benefits from organic resource management extend beyond nutrient supply because of their effects upon soil health and its physical, hydrologic and biological dimensions. The challenge is to place this technical information into a practical context so that it may be disseminated to, and adapted by farmers.

Insufficient recommendations are just one of many factors that preclude the adoption of mineral fertilizers by African small-scale farmers. Farmers lack sufficient working knowledge about fertilizers and sometimes distrust them, have limited access to reasonably priced fertilizers in the needed forms and appropriately packaged and labeled quantities, and cannot reach fair commodity markets and credit structures that encourage further investment in farm enterprises.

Furthermore, most risk averse caution by smallholders is warranted as their household wellbeing is jeopardized by a wrong decision coupled with a poor growing season. Fertilizers must be recommended and promoted within these contexts and the concerns of farmers who remain recalcitrant to their adoption must be addressed in an understanding manner.

ISFM-based advice

Opportunity exists to better target ISFM practices that accentuate the use of mineral fertilizers to more localized agro-ecological and socioeconomic settings. This approach will necessarily provide different recommendations based upon farmers' market orientation. Thus, ISFM can maintain sustainable production in the best-managed fields, enhance and sustain productivity of moderately productive but responsive fields and restore and rehabilitate degraded soils. In general, these options involve judicious management of mineral fertilizers and farmer-available organic resources. But improved recommendations based upon ISFM practice will achieve little by themselves. Farmers' knowledge of fertilizers and their access to them must also be improved. The profits from fertilizer use must be clearly demonstrated to farmers and incentives provided to increase investment in them. Fertilizers do not stand alone, rather new crop varieties more responsive to mineral nutrition, and more tolerant of other stress must be commercialized and promoted as well.

Constraints to improved targeting of soil fertility input recommendations in SSA have been identified as use of blanket recommendations that do not take into consideration farmers diverse socio-economic and biophysical conditions, poor soil and crop management by farmers, lack of sufficient knowledge, limited access to responsive varieties, low and variable rainfall, limited access to stable produce market, limited financial means and access to credit. If we assume for the moment that the degree and types of nutrient limitations are recognized and that technologies to ameliorate that condition are identified, then the next important step is to devise strategies that facilitate the delivery of these technologies to needy farmers. These technologies must be packaged into products and field operations that are recognizable, available and affordable to farm households. In the case of fertilizers, farmers must obtain and apply the correct types at the appropriate time and placement, and then later be satisfied with the resulting crop. Clearly, policy interventions and marketing strategies can improve farmers' access to fertilizers but they will nonetheless remain under-utilized if they appear over-priced or are perceived as risky (see Chapters 19 and 20).

Chapter 13. Dissemination of ISFM technologies

Much has been done in SSA to address issues of declining soil fertility but the results remain limited in relation to the scale of the problem and widely replicable and sustainable approaches are yet to be identified (Murwira 2003). The major constraints to adoption of improved soil fertility input recommendations include lack of awareness of technologies, insufficient adaptation of technologies to farmer conditions, poor research-extension-farmer linkages, land tenure, labor, unfocused institutional support, gender considerations, and the absence or perversion of needed national and regional policies.

Since the 1950s researchers, extension staff and development partners have employed different approaches in their attempts to disseminate agricultural technologies. The transfer-of-technology (ToT) model was predominant in the 1950s and 1960s. ToT was later refined in a context influenced by the Green Revolution. Poverty and hunger were viewed basically as a problem of agricultural productivity. That small-scale farmers did not adopt the technology packages developed at research stations led researchers to conclude that farmers were backward and that success lay in creating a better extension service (Matata *et al.* 2001; Selener 2005). Thus, the Training and Visit System (T&V) of agricultural extension was widely implemented (Selener 2005). In the 1970s and early 1980s, non-adoption, still a problem, was attributed to constraints occurring at the farm level. Farming Systems Research arose as a response, emphasizing research at the farm level to diminish constraints to the adoption of new technologies (Pinheiro *et al.* 1996; Matata *et al.* 2001) because increasing productivity also has socio-economic and environmental dimensions (Saver and Campbell 2001). In the 1990s, researchers accentuated the lack of interaction between researchers and farmers as one of the principal weaknesses in previous developed methods. This marked the emergence and gradual evolution of participatory research, an approach aimed at creating appropriate technologies for small-scale farmers through greater teamwork (Killough 2005; Chambers *et al.* 1989). Whereas research-extension-farmer collaboration is essential, other approaches were employed in a bid to increase adoption of the technologies through better linking farmers to markets as a means of increasing their capacity for investment in farm inputs.

Reaching farmers with target recommendations

Low levels of literacy among the smallhold farmers in SSA are a main constraint to effective communication and dissemination of soil fertility information. In Niger, for example, the literacy rate is as low as 16% whereas the average rate in Europe is as high as 97%. In the 1990s, researchers accentuated the lack of interaction between researchers and farmers as one of the principal weaknesses in the development and dissemination of improved farming methods. Special emphasis was placed upon participation of local people and their communities, especially working with and through groups and building upon their traditional knowledge. For this reason, farmer participatory research and dissemination approaches are preferred in the development of soil fertility recommendations (Chambers *et al.* 1989; CGIAR 2006). Farmer participatory approaches also help determine the acceptability and profitability of a technology before it is promoted at a larger scale. There are numerous participatory methods used in disseminating soil fertility input recommendation technologies (Defoer 2002) including experiential learning, pro-poor market development initiatives and facilitated contract farming.

Obviously, there is no single methodology that fits all situations. The heterogeneity amongst different communities as well as different farmers in the same community calls for combination of the strong points of each methodology in a way that gives best possible impact. Farmer Field Schools (FFS) (Okoth *et al.* 2006) have had profound impact in empowering farmers with knowledge. Introducing the community targeting approach of the Participatory Learning and Action Research methodology (van de Fliert and Braun 2004) can enhance impact not only upon

Table 13.1. Returns to US $1000 invested in the dissemination of ISFM (from Woomer, 2003)

Dissemination option	Audience		Unit cost (US $)
Demonstration and field day attended by	100	participants	10
	500	participants	5
	1000	participants	1
Extension brochure prepared and distributed (1 page)	16667	readers	0.06
Extension booklet prepared and distributed (16 pp.)	2000	readers	0.50
Radio program broadcast (x2)	50000	listeners	0.02
Video documentary recorded and broadcast	20000	viewers	0.05
CD video documentary taped and distributed	200	viewers	5.00
Farmer training conducted (Field School)	50	trainees	20
Each member trains 9 other farmers	500	trainees	2

a small group of target farmers but also to the larger community as a whole. Dissemination of ISFM technologies can also be achieved through intermediary organizations that link farmers to commodity markets. Alternatively, processors interested in the end product of each target group can be mobilized to assure farmers of markets and provide small grants that ensures produce quality. As intervening developmental research initiatives conclude, too often less than desired impacts result unless sustainability mechanisms have been considered. For each methodology that will be adapted, mechanisms must be put in place at project inception to make the exit strategy clear to all participants. A sound technology dissemination and transfer method is one that permits multiple disciplinary team involvement and interactive farmer participation.

Several options are available for the promotion of ISFM among small-scale farmers, each with different costs and audiences (Table 13.1). Demonstrations and field days are often organized by community-based organizations (CBOs) and supported by non-governmental organizations (NGOs) and local extension agents. Field demonstrations are established early in the season and become the main focus of the field day when strong differences in management are apparent. Often, local agro-dealers participate to give product demonstrations. Participants gain firsthand experience in various technologies and receive extension information for later study. Field days are particularly effective if the intent is to distribute samples of seed or fertilizer to nearby farmers for use in the following season. The unit cost per farmer depends upon the attendance, and it is possible for over 500 or more participants to attend a well organized field day. Extension brochures and booklets cost about $0.06 and $0.50 respectively. Brochures may also be summarized as posters for wider viewing at shops, extension offices and field days. Radio and video broadcasts are received by many but the technical content is diluted because of their ephemeral nature and the uncertain nature of the audience. Videos may also be recorded for replay on demand. In some cases, radio and TV broadcasts occur free-of-charge when ISFM proponents serve as guests on regular scheduled talk shows or ISFM events are covered by news programs. Farmer training is a more expensive option, but unit costs are reduced through subsequent farmer-to-farmer instruction. A comprehensive program designed to promote ISFM among smallhold farmers should include several if not all of these dissemination approaches.

To ensure that large numbers of farmers enjoy the benefits of improved technologies and market linkages, several follow-up actions are required. There is a need for alternative market-led dissemination and extension. Agro-dealers and out-grower agencies are particularly well placed to provide extension services. Emphasis must be placed upon community-based approaches, starting with farmer organizations and rural agro-dealer networks as agents for disseminating farm technologies. This investment option needs to implement a communication and knowledge-sharing strategy that ensures joint learning and exchanges among beneficiaries. Considerable research on current knowledge, attitudes and practices of key ISFM stakeholders exist. A participatory identification of issues and forms of communication that influence various stakeholders under different circumstances must be undertaken. Additional information materials must be developed in conjunction with activities designed to raise awareness, technical knowledge or develop the stakeholders' skills.

For widespread ISFM dissemination and scaling-up, there is need to invest in broad partnerships, including farmers' organizations and service providers such as agro-dealers, extension, CBOs and local NGOs for farmer mobilization, capacity building and linking farmers to credit and markets (Spielman *et al.* 2007). Members of such strategic alliances are partners in ISFM leaning and technology refinement as well as those conducting monitoring and evaluation (M&E). According to their areas of specialization, each will play different roles to ensure access to farm input and commodity markets, increased productivity, and the protection of agricultural resources. Regional networks may provide assistance in planning and implementation to facilitate partnerships, capacity building, knowledge management, and M&E. Interaction at the national and regional levels is necessary to obtain support for the adaptation of policy and institutional frameworks that backstop adoption of ISFM (see Chapter 19).

Enabling farmers as ISFM practitioners.

Technical breakthroughs in ISFM mean little in the absence of strategies that expand farmers' access to mineral fertilizers and educate them on improved field practice. If we assume that a large program is installed to improve fertilizer access, then what roles of ISFM education are best undertaken by which agents of development? These agents concerned include agro-dealers, extension officers, NGOs and CBOs, farmer associations, produce buyers, policymakers and agricultural scientists.

Agro-dealers are best positioned to provide printed material to farmers as product information. This product information may be displayed as posters or distributed as brochures containing instructions on ISFM. Agro-dealers also play critical roles in distributing the correct types of fertilizer and participating in credit and voucher programs. Agro-dealers are not well positioned to develop this information material, however, and often deliver customer recommendations based upon available inventory rather than farmers' needs. Many agro-dealers test products on their home farms but seldom organize field days around those tests (Mwaura and Woomer 1999).

Front line extension agents are responsible for advising farmers on production techniques. Most extension agents make good use of available information and training materials, but these tools are generally too few or outdated. The dilemma of agricultural extension in Africa cannot be ignored, nor must unrealistic expectations be placed upon it. To some extent, considerable policy reform is required. Too often, senior officials within agricultural ministries are political appointees who are provided favourable terms of employment while front-line extension agents are civil servants who lack the basic resources necessary to work with and train farmers. But not only is resource allocation an issue, but the sheer numbers of needy smallholders presents a near impossible situation. It is not unusual for 200 agricultural field agents within a district or province to be assigned to 200,000 or more small-scale farming households. Agents thus find it difficult to visit most farms. Available skills and resources limit the capacity of agricultural extension to produce and distribute simple literature on ISFM, and many agents rely upon oral tradition to disseminate information. Systems modeled after developed countries, where extension specialists work with relatively few large-scale clients are clearly flawed within the African context. Extension agents and their supervisors require retraining in ISFM and must be provided with budgets to develop relevant extension materials that facilitate land managers as ISFM practitioners.

Non-governmental and community-based organizations have emerged as powerful forces in rural development, in large part due to the shortcomings in service delivery by formal government extension. These organizations have strong farm liaison skills and serve as excellent conduits of information and sample packages of farm inputs, particularly seeds. CBOs include male and female farmers, youth and environmental groups and Farmer Field Schools (Okoth *et al.* 2006). Often, one NGO coordinates several CBOs within their respective administrative boundaries. NGOs assist CBOs to organize ISFM demonstrations, field days and training courses. NGOs tend to have vehicles while CBOs do not, thus NGOs are important in arranging farmer exchange visits. Difficulties arise when NGOs become ideological or territorial and develop rivalries with one another and government extension (Mukhwana and Musioka 2003). Many NGOs were overly influenced by environmental organizations that distrust and malign fertilizers and other needed technologies. This situation results in part because NGOs have limited capacity to produce their own information materials. Other NGOs are extremely opportunistic, and preach anything that will raise funding. Nonetheless, involvement of NGOs and CBOs within the promotion of ISFM is crucial because they represent agents of agricultural change that are in-place and trusted by the farming community. Increasingly, the capacities of NGOs are improving through the recruitment of staff holding B.Sc. and M.Sc. degrees in agriculture and rural development, and as this trend increases, their capacity to develop and relay locally-relevant ISFM information materials improves.

Farm organizations are the most important focus in developing ISFM practice. In many cases, these organizations have developed from umbrella groups of CBOs and Farmer Field Schools following the awareness that consolidation enables members' expectation for service delivery. These associations range in size from a few hundred to a few thousand members, operate from constitutions, elect officers and maintain headquarter offices. These officers are under pressure from members to provide information on technologies and products, credit, lower-priced farm inputs and engage in collective produce marketing. Farm organizations liaise well with both NGOs and agricultural extension and deal with these other parties as equals depending upon their size and advocacy skills. Organization officers tend to be retired civil servants, teachers and community leaders who are not necessarily skilled farmers, thus need exists for training in fertilizer handling and ISFM. Farm organizations often establish specialized task committees and are characterized by very strong peer pressure among members, who then undertake farm changes that they would be reluctant to undertake as individuals. As service provision grows, the organizations attract additional members, including poorer members of the farming community. Farm associations have weak capacities to develop their own training material and generally rely more upon external instructors to conduct training courses.

Produce buyers sometimes organize out-grower schemes or contract producer associations in ways that facilitate farm input supply and advice to farmers. Usually, these services are intended to meet production schedules and industry standards but they may also be shaped to extend advice on ISFM. Out-growers comprise ready audiences for ISFM practices directed toward cash crops and are better positioned to invest in farm improvements. In many cases, produce buyers are unable to obtain sufficient supplies of pulses, such as soybean and groundnut, and satisfying these markets is another incentive to both ISFM and community-based seed production.

Policymakers should be more aware that ISFM is a vehicle toward food security and rural prosperity. Ironically, many elected policymakers in Africa have rural constituencies but weak knowledge of the agricultural policies that affect them. It is important that fertilizers, agro-minerals, seeds, farm machinery and implements flow across borders as duty-free commodities. Tax incentives should be provided to seed producers and agro-mineral processors. Fertilizer repackaging and labeling laws should flexibly account for the needs of poor farmers and the penalties for product adulteration must be enforced and severe. Extension supervisors that are professional agriculturalists and competitively recruited will likely outperform those who are politically appointed. ISFM should be included within public school curriculum and introduced as a discipline within national universities. Action is required to conduct information campaigns directed at policymakers and follow-up advocacy. To stimulate policy reform, farm associations should become involved in lobbying and political endorsement on behalf of their members.

Agricultural scientists recognize their role in serving society by providing important solutions to pressing problems. This situation particularly holds true for soil fertility management, where traditional farming methods on ancient soils has led to severe nutrient depletion, causing low crop yields that drive the poverty cycle (Breman *et al.* 2005). Slow developmental progress results, in part from Africa's complex agro-ecologies and social dynamics, but also because scientists have not operated with a sense of urgent mission, often preferring to explore peripheral opportunities too far removed from the grasp of smallholders. A new wave of ISFM professionals are now emerging who are truly committed to meaningful impacts at the farm level, understand the legitimacy of market-led technology adoption and value chain management, and also recognize site-specific opportunities for better management of available capital, farm and human resources (Sanginga *et al.* 2007). These professionals are best supported by African national universities and assisted by an ISFM Center of Excellence as proposed in the Foreword and Chapter 21

Farm households must develop a new sense of importance by regarding farming as a profession rather than a last resort. Outsiders can assist by providing information, training, credit and other incentives but the farmers themselves can only break the vicious cycle of poverty through the transition from subsistence to market production and hard work. Indeed, ISFM should be viewed as a means to achieve larger household goals. Farmers should recognize their responsibility to repay loans, but must not be penalized when repayment is not possible because of circumstances beyond their control, particularly following lengthy, severe drought. Africa's poor farmers warrant outside assistance but must also be helpful to one another, particularly towards more disadvantaged community members.

Chapter 14. Designing an ISFM adoption project

Innovative, cost-effective projects may be designed to accelerate the adoption of proven ISFM technologies within rural communities. Such projects may involve relatively few to thousands of farm households, depending upon the available resources, particular technology and agricultural setting. Smaller projects are intended to field test pioneering technologies while larger projects serve to strengthen both rural wellbeing and agricultural value chains (Sanginga *et al.* 2007). Simple spreadsheet utilities may be constructed that serve to guide project design and calculate its impacts. These projects may also be linked to evaluation approaches that monitor soil health.

The ultimate clients of ISFM adoption projects are small-scale farmers seeking to improve their household condition through better crop and soil management but several other clients and partners must be involved as well. Agricultural scientists must identify specific, proven ISFM technology packages that will have a high probability of success under smallholder conditions. Both governmental and non-governmental development partners have an important role to play in terms of assembling inputs and field protocols, distributing them to local organizations and monitoring their overall impacts (Stringfellow *et al.* 1997). Technology packages are best distributed through existing community-based and farmer organizations that provide peer support to participating farm households (Woomer *et al.* 2003). Local groups are also responsible for installing technology demonstrations and conducting farmer field days. ISFM packages are best composed of commercially-available materials obtained from larger farm input suppliers, such as seed producers and fertilizer wholesalers that are repackaged into amounts required by the project (Kelly *et al.* 2003). Local stockists should be invited to farmer field days and encouraged to display their products, and provide incentives to market inputs that are necessary to locally adapted ISFM. It is also important to liaise with agricultural extension agents and other development agencies throughout the project. News media, particularly local radio stations are an effective means to announce field days and report project outcomes.

Scope of operations. Specific operations will vary between ISFM adoption projects but certain general features may be distinguished. First, proven ISFM technologies must be identified based upon recent advances in on-farm research and local agricultural conditions. Often these technologies are identified through ISFM technology planning meetings in which all clients and potential partners describe their needs and experiences (Figure 14.1). Next, these technologies are captured and packaged in terms of farm inputs and field protocols. Again, the size of these packages will vary but it is often better to design more, smaller packages to assure involvement by a larger number of households. Then the technology packages must be assembled, often by teams formed among local cooperators. A well organized team can package many tons of fertilizer and seed within a few days. In other cases, farm input suppliers may be contracted to provide seed, fertilizer and other materials in specified amounts. Information and instructional materials should be translated into local languages and field tested before widespread distribution. Precautions must be taken to assure that inputs, protocols and packages are assembled and distributed ahead of the expected rains because farmers that receive these packages too late often commit their lands to other uses. Technology packages are then sent to supervising collaborators, usually community-based organizations or front-line extension agents, for distribution to farmers (Woomer *et al.* 2003). This is an important step because a roster of participants must be generated for use in baseline studies and monitoring project impacts. These local supervisors are also well positioned to install roadside demonstrations and conduct farmer field days. The range of technical approaches and number of participants may vary as a project develops over time from pilot through intermediate and large scale operations.

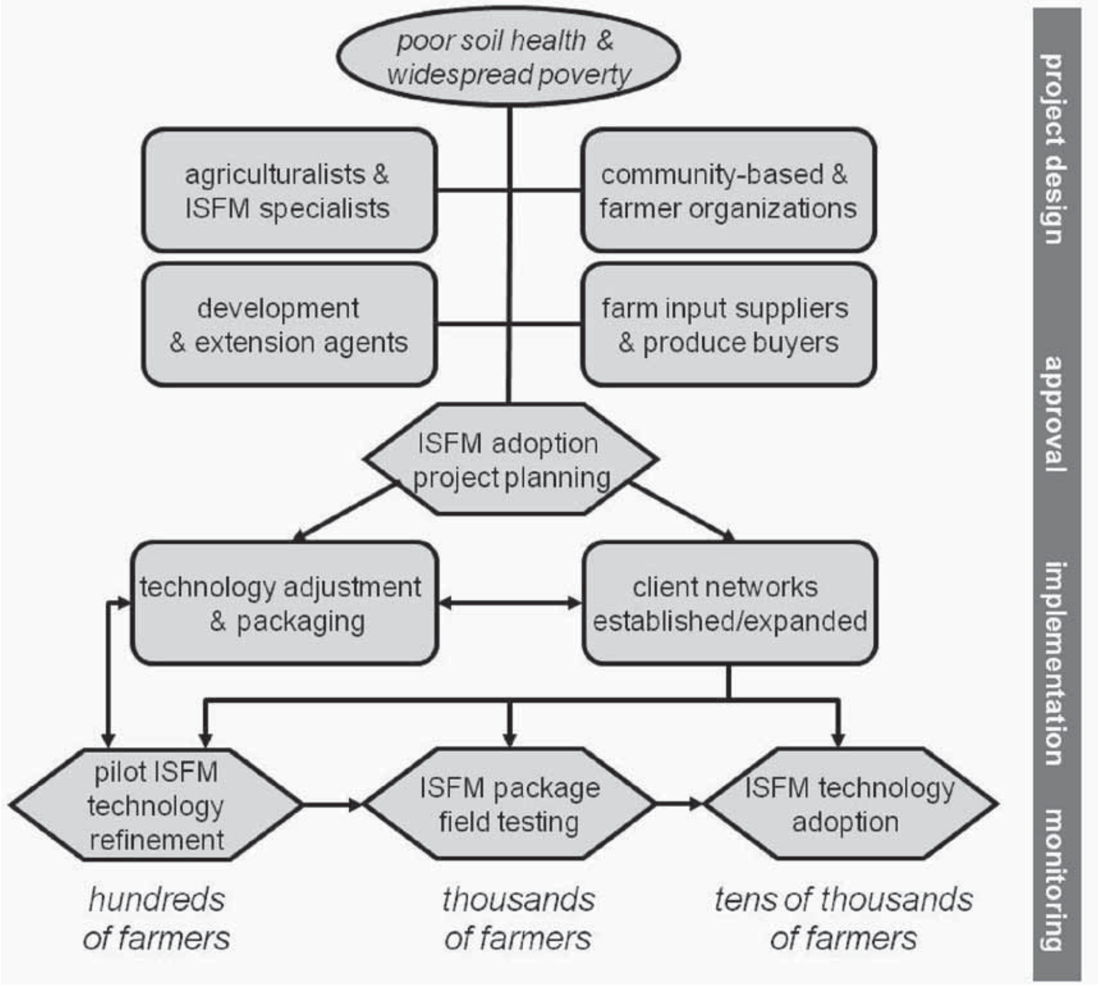

Figure 14.1. The design and operations of an innovative ISFM adoption project based upon proven, packaged technologies channeled to farmer organizations through the private sector.

Pilot technology testing. This stage is intended to examine several candidate technologies on tens to hundreds of farms in order to better focus future efforts (Figure 14.1). Inputs are packaged in amounts that facilitate technology comparisons (e.g. 25 to 100 m^2 plots). Often the field technologies include pre-release testing of new crop varieties or recently developed fertilizers that are not yet commercially available, and are usually compared to current farmer practice and existing recommendations. Participating farmers may be asked to choose between one or more of several candidate land management options and it is important that they are aware that the pilot field technologies not be considered as recommended above existing ones until field testing is complete. In most cases, organic resources examined in the field tests must be common to most farmers, such as crop residues or livestock manures, but under resource-limited conditions, new sources of organic resources, such as multi-purpose legumes, may also be included at this phase of field tests. Crop performance, labor requirements and economic returns of the different options are quantified at this stage of adaptive research with farmers being provided opportunity to refine and combine different practices. It is possible for a small research team and a few farm liaison specialists to conduct this phase of operations. In many cases, past research findings and on-the-shelf technologies can permit development organizations to move directly to intermediate-scale field testing, but care must be taken to advance only proven technologies to willing clients.

Intermediate-scale technology field testing. Intermediate-scale technology testing involves several hundred to thousands of farm households and is intended to introduce and refine a proven land management technology among the farming community (Figure 14.1). Commercially-available inputs are usually packaged in an amount that accommodates a significant fraction of an average farmer's field (e.g. 100 to 500 m^2). The technologies are packaged with accompanying extension information, distributed free-of-charge or at a modest price, and a cross-section of participants later surveyed concerning their impressions and preferences. It is important that local extension agents and community-based organizations be active participants throughout this phase of ISFM development.

Larger-scale ISFM Promotion. This phase of project development is intended to instill sound ISFM practice within the farming community through investment opportunity and other incentives (Figure 14.1). Inputs are packaged in quantities that reflect the size of farm enterprises and fields (e.g. 1000 to 2000 m^2). Literally tens of thousands of farmers are expected to participate in these developmental activities, and the ISFM packages may either be offered on credit through farmer organizations or redeemable vouchers distributed for use at local farm input suppliers. Full participation of both agricultural extension and the private sector is crucial to the success of this stage.

Examples of ISFM packages.

The approach where farm inputs and information packages are assembled and directly extended to farmers in a manner that leads to technology adoption and fuller commercialization of those inputs is flexible in its ISFM targets. These targets are largely goal oriented and some examples follow.

Economize nitrogen management. Insufficient soil nitrogen is the most widespread nutrient deficiency in Africa and satisfying crop demand through large applications of mineral fertilizers alone is not an option for most small-scale farmers (Woomer and Muchena 1996). Furthermore, soil nitrogen is subject to leaching and gaseous loss or biological immobilization so applying labile forms of nitrogen too early in the growing season is inefficient (Smaling *et al.* 1997). Fortunately, nitrogen gains can be realized through biological nitrogen fixation (BNF) and field techniques are available that greatly increase nitrogen-use efficiency. Cultivating legumes as intercrops or in rotation is key to exploiting BNF but it is crucial that soil nitrogen, and not some other nutrient, be limiting for BNF to proceed at its full potential (Giller 2001). This necessitates balanced management of phosphorus, potassium, sulfur, and other possible limiting nutrients (designated P-K-S+). Strategic application of nitrogen fertilizers as top-dressings is another means to synchronize nitrogen availability and crop demand, particularly when applications are timed to moisture availability (Piha 1993). Some additions of top-dressed nitrogen, particularly urea, are best combined with weeding operations to incorporate them into the soil and reduce gaseous loss. The specific suite of nitrogen management technologies varies greatly within different agro-ecological zones and farming systems, but available research findings are usually sufficient to design candidate ISFM packages for refinement, field testing and adoption.

Introduce cereal-legume rotation. Continuous monocropping of cereals has led to declining yields and land degradation. One means to break this trend is to introduce ISFM packages consisting of legume seed and P-K-S+ fertilizer blends that are intended for use in rotation with cereal. These legumes include recently improved varieties of soybean (*Glycine max*), lablab (*Lablab purpureus*), and groundnut (*Arachis hypogaea*). In some cases, the legume seed should be accompanied by rhizobial inoculants (Van Rensburg *et al.* 1976, Woomer *et al.* 1999). In monomodal rainfall areas, legumes may be cultivated during one year in three (Sanginga *et al.*

1997) but in bimodal regimes the legumes can be grown every year during the weaker of the two rains (see Chapter 6). Several accompanying actions may prove necessary including the licensing and production of improved legumes by seed producers, community-based seed production, commercial distribution of non-nitrogenous fertilizers, the manufacture or importation of legume inoculants and the strengthening of legume produce markets.

Mobilize indigenous agro-minerals. Africa is well endowed with a variety of agro-minerals but these materials remain underutilized by small-scale farmers (see Chapter 3). While these materials can potentially offer a lower cost alternative to imported fertilizers, this goal cannot be achieved until mining, processing and packaging operations are undertaken at sufficient scale to guarantee a supply of agronomically effective materials (van Straaten 2002). One means to develop demand for agro-minerals is through ISFM packages that inform farmers about the strengths and weaknesses of agro-mineral use. In the case of processed rock phosphate, packages may target the phosphorus deficient patches that develop in farmers' fields and be accompanied by improved varieties and supplemental N fertilizer (Okalebo *et al.* 2006). Similarly, agro-minerals are central to large-scale nutrient replenishment strategies (Buresh *et al.* 1997). In the case of limestone or dolomite, participants must be provided means to measure soil pH and also be provided access to stress-tolerant varieties. In the case of gypsum, farmers must learn to distinguish sulphur deficiency symptoms of their major crops. Indeed, increased use of agro-minerals by small-scale African farmers requires not only industrial expansion but also well-focused accompanying ISFM technologies (Woomer *et al.* 1997).

Overcome striga. Striga is a parasitic weed that suppresses the response to improved soil fertility management. About 20 million hectares of cropland in sub-Saharan Africa are now infested with striga causing massive crop loss. Maize is particularly susceptible to striga and the parasite inflicts annual grain losses of 1.6 million tons valued at US $383 million (AATF 2006). For several decades, small-scale farmers sought to control striga by hand weeding, but this practice failed because striga causes much of its damage before emerging aboveground (Odhiambo and Woomer 2005). Two new technologies offer greater control of striga, 1) imazapyr seed coating of herbicide-resistant maize seeds, and 2) intercropping or rotation of cereals with field legumes that suppress striga (Kanampiu *et al.* 2002: Khan *et al.* 2005). Striga reduction through crop management is an important determinant of soil health, and ISFM efforts within striga-infested areas must not overlook this opportunity. ISFM packages that suppress striga may contain seeds of field legumes that induce striga germination such as soybean (*G. max*) or desmodium (*Desmodium intortum* or *D. uncinatum*), treated, herbicide-resistant cereals and reduced forms of N, such as urea and ammonium that are assimilated by cereals but cannot be utilized by striga. Striga often appears as patches so the input packages should be adjusted to their size (e.g. 500 to 1000 m^2) (Otieno *et al.* 2005). Pilot testing of these technologies in west Kenya resulted in yield improvement of 785 kg grain per ha, reduced striga expression by 84% and experienced widespread acceptance and overwhelming demand by farmers (Woomer *et al.* 2008). Other improved management strategies that may be captured into technology packages, such as innovative intercropping or combining fertilizer micro-dosing with water harvesting are described in Chapters 7 and 8.

Improving Linkage to Markets

The scope of larger ISFM projects requires that arrangements be made to market surplus production. This connection is necessary because future investments in fertilizer and other purchased farm inputs largely depend upon the likelihood of producing and marketing more crops at a fair profit. Too often, poor grain quality, difficulties and risks of grain storage and overly-complex marketing chains result in the low prices received by small-scale farmers. The key is for farmers to engage in collective marketing to overcome these difficulties.

One form of collective marketing is through the formation of local cereal banks (see Chapter 20). These registered CBOs can serve tens to hundreds of members. Often external assistance is required to form these cereal banks and provide training in group leadership and dynamics, post-harvest quality control, recordkeeping, sales and marketing, and by providing local transportation, quality control services and a modest loan to commence produce trading. Once established, members deposit produce that is bulked, inspected and collectively sold to top-end buyers for higher prices than offered by local middlemen. Securing higher prices may require that produce be sold off-season, either by early harvest and rapid processing or commodity storage (Figure 14.2). Collective marketing by farmer groups enables sales to top-end buyers such as millers, and smaller quantities to local organizations and the general public. Local cereal banks are usually open to the public and sell quantities ranging from 2 kg to local consumers and 10 tons to local schools and hospitals, activities that are important to local food security during annual hunger seasons (Figure 14.2).

Cereals must meet several standards to become eligible for top prices. For example, dried maize in Kenya must not contain more than 13.5% moisture, 3% insect damaged or diseased grains, 2% broken grain and 1% off-color grains and foreign matter. The key to meeting these standards depends upon proper shelling, drying and storage. Excess moisture and rotting grain are the most crucial factors immediately after harvest, while pest damage usually appears several months after harvest. Farmers, who indiscriminately shell every cob, then dry their grain on the open ground and bag it without dusting for insects stand little chance of meeting these industry standards. On the other hand, farmers that reject diseased or insect infested cobs, dry on tarpaulins, screen away fine foreign matter when necessary, inspect grains prior to bagging and dust against weevils and borers can produce premium grade maize. Short training courses offered to small-scale farmers can greatly improve grain quality the following season as illustrated by an example from Kenya (Table 14.1). The quality of smallholders' grain can excel that of large commercial farms because hand shelling and sorting better differentiate grain than when it is machine harvested and shelled. Seed treatment and fumigation of stores provide near complete control of borers and weevils for several months, while no action too often results in large loss.

Collective action is the key to improve the market access and experience of poor farmers. Smallholders, acting as individuals, can neither produce the quantities necessary to enter the larger, more reliable markets, nor access current information about, or transportation to those

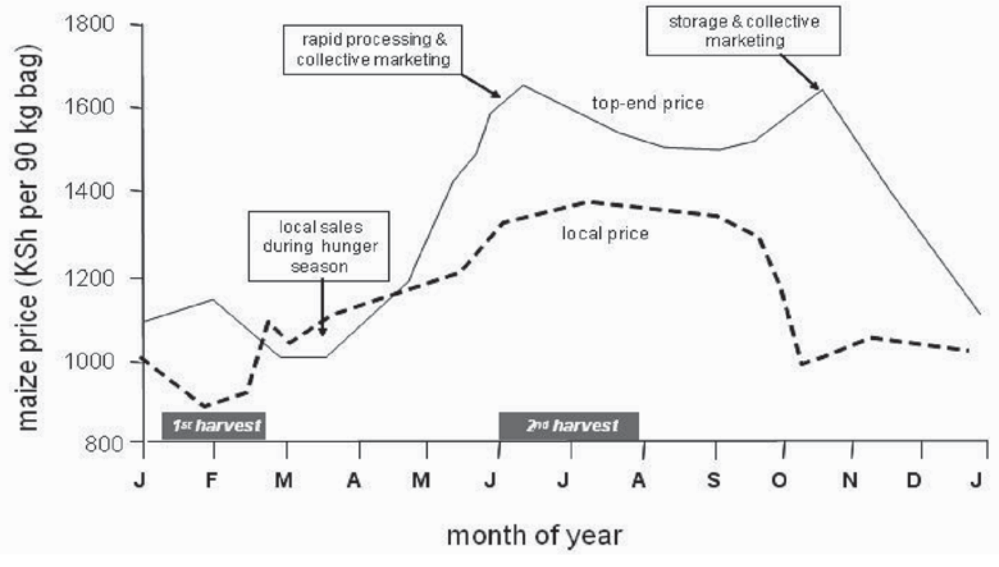

Figure 14.2. Price trends and marketings strategies for maize in west Kenya, an area with bimodal rainfall.

Table 14.1. Maize grain industry standards and quality before and after training in grain processing provided to smallholders in west Kenya.

	Moisture content	Diseased & discolored	Insect damaged	Broken	Foreign matter	Off color
	%					
Industry standard	<13.5	<3.0	<3.0	<2.0	<1.0	<1.0
Without training	12.4	4.7	5.6	1	1	0.6
After training	12.5	0.9	1.2	0.2	0.6	0.3

markets. Farmers themselves ought to form and participate in strong, local marketing associations in order to receive a fairer value for their produce. Reducing the control held by opportunistic middlemen requires that farmers develop greater market intelligence and address farming as a business. The poorest farmers risk becoming bypassed if special effort is not made to include them within local cereal banks. Ways to involve the poorer members of the community include setting membership dues and minimum grain deposits very low, or waiving them altogether and returning some fraction of dividends from cereal bank profits to all members regardless of their level of commodity participation.

Projecting Impacts

A process may be followed to design ISFM adoption projects that includes 1) identifying the project clients and target land area, 2) calculating the cost of needed farm inputs and accompanying ISFM services, 3) establishing current production baselines and the response to currently recommended practices, 4) identifying the value addition through ISFM, and finally 5) projecting the overall returns to investment of the project and the benefits to individual participants.

Project clients and area. Few projects can afford to be open-ended in terms of participation because of the limitations to project resources and increased variability across larger areas. Past experience suggests that it is difficult in terms of administration, logistics and technical appropriateness for a single project site to engage more than 5000 to 25000 farming households. Larger projects should operate from multiple locations. One means to pre-establish the size of a project is to identify the number of target participants and their field size over which ISFM interventions will focus. By combining these two factors, the total project area may be calculated. For example, a project empowering 5000 households to develop ISFM practice on 2000 m^2 each (or ½ acre) covers a total area of 1000 ha.

Project costs. Project costs consider the price and amount of needed farm inputs and accompanying ISFM services. Costs are based upon the price of inputs necessary to achieve a proven ISFM intervention including fertilizers, seed and other materials. Fertilizer rates may be adjusted by deducting the target from current farmer practice but in many cases the fertilizer use by small-scale farmers is practically nil. When input costs are calculated per household, then project input costs may be readily calculated. In general, farm inputs require about $5 to $20 per 1000 m^2. ISFM services include the costs of developing and distributing extension information, conducting field and other promotional activities and monitoring project impacts. These services typically require $2 to $20 per household and season depending upon project size and the scope of the ISFM intervention. In this way, a project involving 5000 household on 2000 m^2 over two cropping seasons requires $120,000 to $420,000 depending on the target ISFM intervention.

Table 14.2. Fertilizer consumption and the current and realistic target yields of maize, millet and cassava in five sub-regions of Sub-Saharan Africa. The potential yields are based upon on-farm ISFM approaches (after FAO 2005).

African	fertilizer	maize yield		millet yield		cassava yield	
Sub-region	consumption[1]	current	target	current	target	current	target
	---------- kg ha^{-1} ----------						
Central	0.9	798	2455	673	1709	8032	12175
East	15.3	1631	2945	1287	2108	12256	15540
Sahel	5.5	1516	3065	665	1633	7523	11395
Southern	16.7	1168	2447	617	1416	7347	10544
West	5.9	1143	2683	987	1950	10406	14255

Much of these costs may be recovered and recycled by extending the farm inputs on credit to participating households.

Baseline yields and returns. Baseline information is required to identify areas where ISFM interventions are required and to project the likely returns from project efforts. In general, crop yield records permit calculation of current production and, when combined with commodity price, then crop value may be derived (Woomer 2007). Current crop yields in different African sub-regions are presented in Table 14.2. Similarly, it is important to understand the yields and returns resulting from current fertilizer recommendations. Yield may be projected by multiplying the recommended rate (kg fertilizer nutrient per ha) and agronomic efficiency (kg crop per kg fertilizer nutrient) and adding this to baseline yields. Factoring the fertilizer price permits calculation of baseline economic returns and benefit to cost ratios.

ISFM value addition. The purpose of an ISFM intervention is to increase yield and farmer's return through improved land management practice. This may be achieved by improving upon the rate, form and placement of fertilizers, making better use of available organic resources and new crop attributes, skillful combination and rotation of crops, basic land conservation measures and combinations of these strategies. To project these gains, the amounts of mineral and organic nutrients applied or recycled and their agronomic efficiencies may be combined to calculate improved yield, increased production, increased returns and the benefit to cost ratio resulting from ISFM interventions (Woomer 2007). Some yield targets resulting from ISFM interventions in five African sub-regions are presented in Table 14.2.

Overall investment summary. From the above information it is possible to develop a summary of the projected investment based upon the total costs (input costs + ISFM services), the expected gross returns (increased yield x commodity price), net returns (gross returns – total costs) and the benefit to cost ratio (gross returns/input costs). It is equally important that the benefits per household be projected in terms of increased inputs accessed, their value, resulting increase in crop value and the economic returns per household.

Summarizing an ISFM adoption project

A spreadsheet was constructed based upon the design approach described above (Table 14.4) that introduces ISFM technology to 5000 households and managing 1000 ha. In this project, fertilizer use is raised to 50 kg ha^{-1} and reinforced with ISFM approaches. Project input costs are \$120,000 and ISFM services (and project administration) is \$12 per household, or \$60,000, resulting in total project costs of about \$180,000. Current crop yields are only 1 t ha^{-1}, and when combined with improved seed, greater agronomic efficiency of fertilizer and improved residue management, is

Table 14.3. A spreadsheet useful in the design and projected impacts of an ISFM adoption project involving 5000 households over one season.

Project clients and area	
number of households (no)	5000
area per household (ha)	0.2
total project area (ha)	**1000**
Input and ISFM costs	
current fertilizer use (kg/ha)	8
target fertilizer use (kg/ha)	50
fertilizer price ($/kg)	$2.15
fertilizer nutrient cost ($/household)	**$18.06**
other input costs ($/household)	$6.00
total input costs ($)	**$120,300**
ISFM services ($/household)	$12.00
ISFM promotion costs ($)	**$60,000**
total project costs ($)	**$180,300**
Baseline yields and returns	
Current yield (t/ha)	1
Current production (t)	**1000**
Commodity price ($/t)	$220
Current value ($)	**$220,000**
Conventional fertilizer yields and returns	
CF AE (kg/kg)	12
CF yield (t/ha)	**1.50**
CF production (t)	**1504**
CF increase value ($)	**$110,880**
CF benefit:cost ratio	**2.75**

ISFM value addition	
ISFM AE (kg/kg)	32
ISFM input (kg FE/ha)	16
ISFM yield (t/ha)	**2.86**
ISFM production (t)	**2856**
ISFM increase value ($)	**$297,440**
ISFM benefit:cost ratio	**4.96**
Overall investment summary	
Total costs ($)	**$180,300**
Gross returns ($)	**$408,320**
Net return ($)	**$228,020**
Overall benefit to cost ratio	**2.26**
Benefits per household	
additional fertilizer inputs (kg)	**8.4**
input value ($)	**$24.06**
crop increase (t)	**0.37**
crop value ($)	**$81.66**
household net return ($)	**$57.60**
HH benefit to cost ratio	**3.39**

increased to 2.9 t ha^{-1}. The overall project produces over 4,300 tons of food at a benefit to cost ratio of 2.3. Individual households produce an additional 370 kg of yield through introduced ISFM technologies at a very acceptable benefit to cost ratio of 3.4, encouraging adoption and future investment. This scenario does not account for repayment by farmers and reinvestment in farm inputs during the following cropping season, nor does it account for marketing services. Nonetheless, the potential for modest ISFM adoption projects is clear and, when such projects are aggregated, they can have a profound impact upon regional food supply and rural wellbeing.

Skeptics argue that the assembly and distribution of ISFM packages described in this chapter have many shortcomings. Some believe that farmers should not be provided inputs free-of-charge as this creates dependency. Others suggest this approach is too top-down, with farmers serving to test but not design needed technologies (Lacy 1996). Another argument is that the private sector is engaged too late in the process and that farmer associations should not be supported to supply farm inputs as this undermines efforts to build commercial supply networks. Most of these arguments are ideological in nature and do not take into account the pragmatic success this approach has achieved in working with African smallholders (Eicher 1999). When proven ISFM technologies are distributed to farmers as input packages sufficient to plant 100 to 400 m^2, they discover new and better ways to manage their land resource. When this action is followed by offering the same technology on credit, farmers are provided incentives for investment. Charges of top-down process are also not valid because that criticism largely rests with how the ISFM technology is identified and refined in the first place and not with how it is later packaged and disseminated. Keeping in mind that customer feedback is its own participatory mechanism, farm input manufacturers and suppliers can be expected to operate in a commercially advantageous manner. Private sector participation is best kept open-ended because the overall goal is to empower farmers to combine their available resources and purchased farm inputs in a more cost-and-labor effective manner so they can escape from household poverty and rural stagnation, not to protect the interests of relatively few entrepreneurs. Finally, arguments that private sector growth is inhibited by input distribution through farmer organizations is secondary to the goal of expanding farmer collective action. Farmers that collectively purchase inputs and market surpluses are in a better economic position than those who do not, and the private sector must adapt to this reality. Clearly, now is the time for innovative advances in soil fertility management and the rapid dissemination of proven technologies, and the ISFM package approach described in this Chapter meets both criteria.

Monitoring soil health

In order to assess the full impacts of an ISFM adoption project, it is important to monitor soil health and its improvement. In order to do so, a suite of practical indicators must be developed, soil baseline conditions established and then the soil monitored over time based upon landscape, physical, chemical, biological and land management criteria applicable to small-scale farms. The following criteria provide means for rapid assessment and ranking of soil health based upon observations of landscapes, surface water, soils, plants and beneficial soil organisms.

Landscape criteria. The proportion of exposed soil within the farm is an important, rapidly estimated indicator because exposed soils are more susceptible to erosion and compaction. This criterion is expressed as a percentage of total farm area using walking transects, and measurements should not be taken early in the cropping cycle before crop canopies have closed. Exposed soil may be ranked as widespread (0), frequent (1), occasional (2) and absent (3).

Severity of soil erosion. Both water and wind erosion compromize soil health. This criterion is expressed as a percentage of total farm area using walking transects. Extreme erosion signals the need of land restoration rather than ISFM. Soil erosion may be ranked as severe (0), moderate (1), slight (2) and absent (3).

Presence of contour structures. When fields are sloped, structures built along the contour are necessary to control soil erosion. These structures may be terraces, bunds, rock and trash lines, hedgerows or grass strips. The presence, length and distance between contour structures are important indicators of soil conservation awareness. Contour structures may be ranked as absent (0), distant (1), regular (2) and complete (3). These criteria have little meaning on level ground but increase in importance as cultivated slopes become steeper. Experience is required in assessing the effectiveness of different structures when assigning ranks. For example terraces and bunds are more effective barriers than trash lines, poorly established hedgerows or narrow grass strips.

Protection of riparian strips and water quality. Cultivation up to the edge of waterways invites soil erosion and at least 2 or 3 meters of vegetation is required under most conservation by-laws. This vegetation provides the greatest service when it consists of both trees and complete understorey. The width of riparian strips may be either scored or measured by tape or measuring sticks. In addition, well protected streams are clear and poorly protected streams are usually muddy. In this way, water quality can be either scored or quickly measured as the length of visibility using a ruler. Riperian strips may be absent (0), narrow (1), compliant (2) and copious (3). Water quality may be muddy (0), cloudy (1), opaque (2) and clear (3).

Chemical and physical criteria. Nutrient deficiency symptoms offer quick insight into soil fertility status. These deficiency symptoms are closely related to the metabolic role of different nutrients and their physiological mobility within the plant (see Chapter 11). While these deficiency symptoms may vary between plants, general traits are usually expressed across most crops (see Table 11.2). Plant deficiency symptoms may, however, be confounded with one another and by moisture stress, waterlogging and plant pathogens, so they are best interpreted with caution and calibrated through soil testing. Nutrient deficiency symptoms may be ranked as severe (0), moderate (1), occasional or slight (2) and absent (3)

Soil acidity. Low soil pH serves as an indicator of nutrient base status (potassium, calcium and magnesium) and results in altered availability of many micronutrients (see Chapter 11). Soil pH below 5.5 results in the solubilization of toxic aluminium. Soil acidity is readily measured using litmus strips, inexpensive hand held instruments and by portable soil test kits and is corrected by applying agricultural lime. Soil acidity may be scored as extreme (<4.5), severe (4.5-5.5), moderate (5.5 to 6.5), neutral (6.5-7.2), assigned values of 0, 1, 2 and 3 respectively. This ranking does not take into account alkalinity (pH >7.2) nor the acid-tolerance of many crops.

Soil organic matter and fractions. Soil organic matter (SOM) provides better nutrient relations and water holding capacity and results in aggregate stability. Soil carbon is measured in the laboratory by acid digestion-calorimetric analyses or using complex instruments that are not well suited to rapid assessment of soil health. Two SOM fractions, microbial biomass C and particulate organic matter indicate the short and mid-term dynamics of organic matter additions to soil, but require more complex measurement. A portable, handheld device that measures soil carbon based upon spectrography has recently become commercially available. Because clay stabilizes soil carbon within organo-mineral complexes, SOM content is not comparable across soils with contrasting textures. Nonetheless, acceptability thresholds of soil carbon may be developed for soils of different textures (sand, silt and clay, and its combinations).

Aggregate stability and water-filled void space. Stable soil aggregates resist erosion and permit a healthy combination of air and water within soil void space. Both of these measurements are conducted using carefully collected soil cores and straightforward analytical procedures within the soil physics laboratory. To a large extent, these properties are dependent upon mineralogy and soil texture so comparisons across different soil types have little meaning. While important indicators of soil health, these laboratory measurements are difficult to include within rapid field assessment.

Biological criteria. In its most holistic context, soil health embodies more than living organisms, but it does not overlook them. The diversity and function of soil microorganisms is fascinating and extremely difficult to assess in the field (or even in the laboratory), but the presence and degree of selected beneficial and detrimental organisms can be described through careful and experienced field observation.

Legume root nodulation. The presence and effectiveness of rhizobia, the microsymbiont associated with nitrogen-fixing legumes, may be inferred by the abundance, size and interior coloration of root nodules. No nodules imply that the host's specialized rhizobia are absent. Sporadic, small nodules with white interiors suggest that infective rhizobia are present but are not symbiotically active. Legumes require inoculation when soil rhizobia are absent or ineffective. 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 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. A key to ISFM is to promote BNF so that its products result in acceptable legume yields and offer residual benefits to following crops. Legume nodules may be scored as absent (0), sporatic (1), abundant (2) and, as occasionally observed, super-abundant (3) and their interiors may be rated as white (0), pink (1), red (2) and dark red (3). Experience is required in this evaluation because legumes have typically different nodule shapes and sizes and, as effective nodules age their interior colour changes.

Presence of soil macrofauna. Soil macrofauna are important indicators of soil health because their activities accentuate soil physical properties and nutrient recycling. Foremost indicators of soil fauna are the presence of earthworms and large soil grubs (insect larvae). Termites are important soil engineers but also attack crops, trees and wooden structure and represent a mixed blessing. Farmers are often indirectly aware of the benefits of soil fauna because they associate them with more productive fields but are also aware of destructive insects. Again, this diagnosis requires caution and experience because some soil insects feed upon seedlings and plant roots. Soil macrofaunal populations may be rated as detrimental (0), largely absent (1), present (2) and active and abundant (3). Detailed information on quantifying soil fauna may be obtained from Moreira *et al.* (2008).

Severity of parasitic plants. Striga is a serious parasite of cereal crops in the Lake Victoria Basin, and elsewhere in sub-Saharan Africa, and its presence is an important indicator of soil health because severely infested hosts do not respond well to soil fertility management. When left unmanaged, striga seed banks may massively accumulate, exceeding one billion seeds per ha and resulting in greater than six parasitic stems per crop plant. Striga management is not well addressed by classical Integrated Pest Management approaches rather it is more subject to agronomic management of crop varieties and combinations, tillage and weeding operations and nitrogen and organic resource management. Reducing striga infestation is a primary goal in achieving soil health within affected soils and the means to achieve this end rests in ISFM. Striga seed banks are quantified in soils using complex and labor requiring elutriation-density separation-counting procedures (Odhiambo and Woomer 2005). Host cereals may be scored as striga stems absent (rank = 3), infrequent (rank = 2, less than one per plant), frequent (rank = 1, one or two per plant) and abundant (rank = 0, more than two stems per plant). Striga is well developed within 10 weeks of crop emergence and care must be taken not to confound lower scores with recent weeding operations.

Severity of root disorders. The presence of root disorders is an important diagnostic tool that may contribute to the rapid assessment of soil health. Roots are subject to attack by nematodes and parasitic fungi and bacteria, but one needs not know the causal organism to ascertain that root systems are not well developed. Root disorders vary among crops, with some being resistant and others chronically affected. Common bean (*P. vulgaris*) serves as a useful indicator of root disorders because it is subject to such a wide range of pests and diseases, and their shallow root systems are rapidly recovered and evaluated. A visual ranking of root disorders may include severely stunted, galled or rotten roots (0), stunted, underdeveloped roots (1), roots expressing occasional lesions, galls or necrotic tips (2) or healthy, well developed root systems (3). Evaluators must realize that short-term drought, waterlogging and aboveground plant health greatly affect root systems as well.

Farm management criteria. The handling and application of organic resources and mineral fertilizers are important factors in soil health. These materials include crop residues and their utilization, composting, manure management, pre-plant fertilizer application and nitrogen top-dressing. It is difficult to gauge a farmer's organic resource and mineral fertilizer handling procedures from a single visit without queries of season-long practices. For this reason, rapid information is best collected through participatory group discussion rather than formal on-farm survey.

Crop residue management. Applying crop residues to soils through incorporation and mulching promotes nutrient recycling, improves fertilizer use efficiency, contributes to soil organic matter and feeds soil biological processes. Feeding residues to domestic animals and then applying their manure has a similar effect. Alternatively, those who burn residues, sell them to others or discard them along field boundaries are wasting opportunity. The use of crop residues is therefore an important indicator of soil health. Crop residue use may be rated as wasteful burning discarding or sale to others (0), retained in field or fed to livestock (1), collected then re-applied (2), processed, nutrient fortified and applied in conjunction with mineral fertilizers (3).

Composting. Composting is a means to bulk and store organic resources and to concentrate their nutrients. Composts may be fortified with lime, fertilizers and agro-minerals (see Chapter 4). Typically, fertilizers are applied to higher-value crops or used within potting mixtures and seedling beds, but when available in adequate amounts, one ton of fertilizer may be substituted for about 100 kg of mineral fertilizer. Composting may be ranked as follows: no compost produced (0), small piles or pits for home garden (1), large compost piles intended for field crops (2), covered, watered, layered compost piles receiving fortification with minerals (3).

Table 14.4. A checklist approach to assessing soil health developed in conjunction with an ISFM development program.

Category and Indicator	Ranking	Score
Landscape criteria		
Proportion of exposed soil	widespread (0), frequent (1), occasional (2), absent (3)	
Severity of soil erosion	severe (0), moderate (1), slight (2), absent (3)	
Presence of contour structures	absent (0), distant (1), regular (2), complete or no slope (3)	
Protection of riparian strips	absent (0), narrow (1), compliant (2), copious or no riparian strip (3)	
Surface water clarity	muddy (0), cloudy (1), opaque (2), clear or no surface water (3)	
Landscape sub-total		
Nutrient deficiency symptoms		
Basal leaf chlorosis and drop	severe (0), moderate (1), occasional or slight (2), absent (3)	
Purpling of lower leaves	severe (0), moderate (1), occasional or slight (2), absent (3)	
Marginal leaf necrosis	severe (0), moderate (1), occasional or slight (2), absent (3)	
Basal interveinal necrosis	severe (0), moderate (1), occasional or slight (2), absent (3)	
Apical chlorosis or tip distortion	severe (0), moderate (1), occasional or slight (2), absent (3)	
Symptom sub-total		
Chemical & physical criteria		
Soil acidity	extreme <4.5 (0), severe 4.5-5.5 (1), moderate 5.5-6.5 (2), neutral 6.5-7.2 (3)	
Biological criteria		
Legume root nodulation	absent (0), sporatic (1), abundant (2), super-abundant (3)	
Nodule interior color	white (0), pink (1), red (2), dark red (3)	
Soil macrofauna	detrimental (0), largely absent (1), present (2), active and abundant (3)	
Striga infestation (stems/plant)	>2 per plant (0), 1-2 per plant (1), <1 per plant (2), absent (3)	
Root disease (see key for details)	severe (0), moderate (1), occasional (2) healthy (3)	
Root galls (see key for details)	severe (0), moderate (1), occasional (2) healthy (3)	
Biology sub-total		
Farm management criteria		
Crop residues (see key for details)	wasteful or sold (0), retained (1), collected (2), processed or fed (3)	
Composting (see key for details)	none (0), small piles (1), large piles (2), covered and fortified (3)	
Manure management (see key)	absent or wasteful (0), haphazard (1), regular (2) processed (3)	
Pre-plant mineral fertilizers	none (0), ≥75 kg ha^{-1} applied (1), 75-150 kg (2), >150 kg (3)	
Top dressed nitrogen fertilizers	none (0), applied once (1) applied twice (2), applied thrice (3)	
Farm management sub-total		
Grand Total		

Manure management. Manure management is a critical component of ISFM in small-scale mixed farming systems and an important indicator of soil health. Cropping provides feed to animal enterprises that in turn produce manure that supply organic inputs and plant nutrients. The value of manure is largely dependent upon how it is collected, stored, combined with other materials and spread. For example, a cow produces about 700 kg of dried manure per year that is equivalent to about 50 to 100 kg of fertilizer depending on how well it is protected from nutrient loss through volatilization and leaching. Manure management may be rated as sold to off-farm buyers, unmanaged or no livestock (0), periodically gathered and haphazardly spread (1), regularly collected, piled and systematically spread (2) and collected daily, separated into urine and faeces, stored under covered conditions and or used in composting operations (3).

Pre-plant mineral fertilizers. Mineral fertilizers are an efficient means to supply plant nutrients and replenish nutrient loss. Fertilizers contain nutrients in concentrated form and are convenient to apply and many forms, such as N and K, are mobile within the soil. The returns to fertilizer use are predictable although by no means certain due to a myriad of risks including drought, extreme precipitation and fluctuating commodity prices. Nonetheless, pre-plant fertilizer use is a cornerstone to improved crop productivity and the maintenance of soil nutrient health, and may be simplistically scored as none applied (0), ≤75 kg ha^{-1} applied (1), 75-150 kg ha^{-1} applied (2), and >150 kg ha^{-1} applied (3). This ranking system does not take into account the fertilizer form, crop demand or compliance with extension recommendations and can be adjusted to better meet local conditions.

Top-dressed nitrogen fertilizers. Small-scale farmers, even those who apply pre-plant fertilizers, seldom perform nitrogen top-dressing. Briefly, nitrogen is a mobile nutrient, readily assimilated and subject to loss through leaching, runoff and volatilization and farmers who apply nitrogen mid-season receive strong returns. Top-dressed nitrogen addition is inherently less risky because it is not applied to failing crops and can be timed with rainfall but its application is required at a time when most farm households are usually short of cash. A ranking of N top-dressing is no top-dressing applied (0), N top-dressing of ≈50 kg CAN or ≈25 kg urea applied once (1) N top-dressing applied twice (2), and N top-dressing applied thrice (3).

Soil Health compilation. The above criteria for field assessment of soil health are generalized and raised to illustrate that practical diagnoses may be monitored in conjunction with an ISFM development program. These criteria are not exclusive and additional observations concerning tree, pasture and fallow coverage and agro-biodiversity may also be useful. So too could criteria be weighed to reflect importance with different agro-ecosystems. Based upon the criteria raised in this sub-section, a possible soil health checklist appears in Table 14.4. Possible values range between 0 and 66 with scores <30 indicative of poorly managed and degrading systems and those >50 are well managed with possibilities for improvement. The importance of many of these criteria is described in further details within Chapter 15.

Chapter 15. ISFM at farm and landscape scales

Too often soil fertility management research is conducted only at the plot or field scale, where interactions among various agricultural enterprises and other land uses are seldom considered. Although most of the current research strength in SSA remains at the plot level, the diversity of forces impinging upon it naturally draws attention towards a hierarchical or nested systems-based approach that is extended to higher scales, particularly the whole farm and landscape. The rationale for working at the farm scale is the need to improve nutrient use efficiency through better allocation of limited organic and inorganic resources among different enterprises, taking into consideration inherent soil variability within the farming system (Okalebo *et al.* 2003, Vanlauwe *et al.* 2006). Inadequacies in supplies of both organic and inorganic nutrients have created strong fertility gradients even within the smallest farms. Smallhold farmers typically remove harvest products and crop residues from their food producing outfields and devote their scarce soil inputs to their smaller market infields, resulting in large differences in soil productivity over time between these two field types. Understanding how to manage the limited nutrient supplies across such fertility gradients is a key component in raising productivity in fields of staple crops. In most regions, fertilizer recommendations remain focused on the maximum yields attainable for broad agroecological regions (see Chapter 1), whereas localities, farms and farmers' production objectives are highly heterogeneous. Fertilizer response by crops also varies with soil type (see Chapter 2). For example, P is a limiting nutrient in a Nitisol while N is the most limiting nutrient in Vertisol (see Table 2.4). These results point to the need to effectively target fertilizer to ensure use efficiency on the different soil types occurring within an agricultural landscape.

Different fertilizer responses have been observed in various parts of the same field due to soil fertility gradients. Prudencio (1993) observed such fertility gradients between the fields closest to the homestead and those furthest. Fofana *et al.* (2006), in a study in West Africa, observed that grain yields averaged 0.8 t ha^{-1} on outfields and 1.36 t ha^{-1} on infields. Recovery of fertilizer N varied considerably and ranged from 17 to 23% on outfields and 34 to 37% on infields. Similarly, average recovery of applied fertilizer P was 31% in the infields compared to 18% in the outfields. These results indicate higher inherent soil fertility and nutrient use efficiency in the infields compared to the outfields and underlines the importance of soil organic carbon and secondary and micronutrients in improving fertilizer use efficiency. Once soils are degraded and depressed in organic matter, the response to fertilizer is lower and the recovery of applied fertilizers is reduced.

Land degradation and environmental services, particularly hydrological response and soil erosion control, can be managed effectively only at larger landscape scales. Research at the watershed scale is critical in tropical regions. Given that soil fertility decline, land degradation and climate change profoundly affect SSA and taking into account projections that the Sahel, East and Southern Africa will be critically short of water in the coming decades, extending ISFM's agenda to different spatial and temporal scales is an extremely important and challenging area for research and development.

Preventing land degradation

Agricultural activities affect and are affected by the quality of the environment. Stigmatized because of over-utilization in intensive agricultural systems elsewhere in the world, fertilizer use in SSA is extremely low (8 kg ha^{-1}). On a global scale, Mosier *et al.* (2004) calculated that next to global mineral nitrogen of some 86 million metric tons (2001 data); man-induced biologically-fixed N caters for another 20 million, and organic waste recycling for another 28 to 36 million tons per year. Harvested crops and their residues currently take half of all anthropogenic N inputs on croplands. Losses to the atmosphere are estimated at 26 to 60 million tons, whereas ground and surface water bodies receive between 32 and 45 million tons from leaching and erosion.

These figures are yet to be determined for SSA. In contrast to these issues associated with nutrient oversupply, however in Africa, harvesting without nutrient replacement has led to a depletion of soil fertility, with serious consequences for human nutrition and the environment as indicated by the Millennium Ecosystem Assessment (MEA 2005). Hence, returning nutrients as mineral fertilizers or from organic or atmospheric sources may be excessive or unbalanced leading to pollution in developed countries or may be insufficient resulting to soil degradation as in SSA. Under most MEA scenarios, 10-20 percent of grassland and forest is projected to be converted between 2000 and 2050, primarily to agriculture. This projected conversion is concentrated in low-income countries and dryland regions. IFDC (2006) indicates that some 50,000 hectares of forest and 60,000 hectares of grasslands in SSA are lost to agriculture annually, and approximately 70 percent of deforestation is a result of clearing land for cultivation. Hence, the third pressure on ecosystems is manifested through land use and cover change.

Insufficient use of fertilizer in SSA has a greater negative effect on the environment than does its use. Non-use of fertilizers in SSA contributes to many different forms of land degradation including removal of natural vegetation, soil physical degradation, soil fertility depletion, wind, and water erosion, and negatively affects biodiversity and carbon sequestration (Jindal 2006). In ancient African soils, fertility is strongly influenced by its organic matter content. Destruction of riparian forests, wetlands, and estuaries allow unbuffered flows of nutrients between terrestrial and water ecosystems. Nitrogen derived from removed vegetation could alternatively be a source of pollution of ground water but this has seldom been quantified. Avenues towards increased, environmentally benign use of fertilizers are advocated at different scales raging from farm to large landscapes. Room for improvement lies in the understanding and valuation of tradeoffs between economic and ecological goals, in quantifying and realizing synergies at the country, landscape, and village scales; and in rewarding land users for maintaining non-market ecosystem services. Efficiency gains in fertilizer based upon using them on the best soils and with the best management render them far more profitable. Fertilizer use in Africa has to be increased significantly, preferably in a context of ISFM aimed at inter-linkages between crops and livestock, between cash and food crops, and landscapes and time. The following processes of nutrient depletion, acidification, organic matter decline and pollution illustrate the interactions between ISFM and the environment at different scales.

Nutrient depletion. In sub-Saharan Africa, outputs tend to be greater than inputs for all nutrients. A continental study pointed to that direction (Stoorvogel *et al.* 1993) and was to a large extent confirmed by case studies at lower spatial scales. Figure 15.1 provides the summary outcome of N for the continent. An average of 22-26 kg N is lost per ha per year, mainly due to removal of harvested product (OUT 1) and erosion (OUT 5). Mineral fertilizer alone (IN 1) is less than half of the nutrients withdrawn via harvested products (OUT 1). Hence, nutrient mining is a reality within sub-Saharan Africa. Cash crops tend to be much less depleting than food and fodder crops. Either they receive more fertilizer and manure (coffee, cotton), or they are deep rooting tree crops that better protect

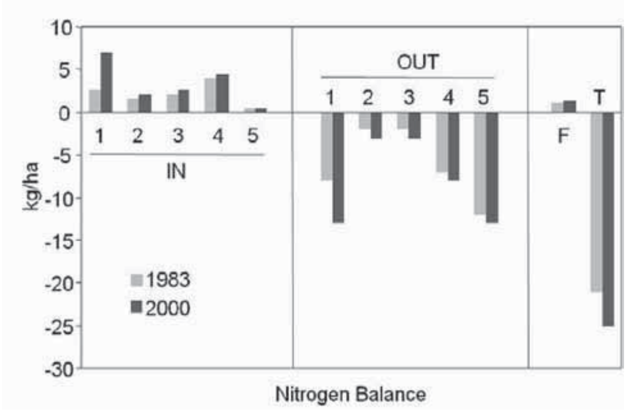

Figure 15.1. Nitrogen balance in Sub-Saharan Africa (Stoorvogel *et al.* 1993). Inputs (IN) 1=Mineral fertilizer, 2=Organic inputs, 3=atmospheric deposition, 4=biological N fixation, 5=sedimentation. Outputs (OUT) 1=harvest products, 2=crop residue residual, 3=leaching, 4=gaseous loss, 5=runoff and erosion.

the soil against fertility loss (cocoa, oil palm). Table 15.1 illustrates that cash crops can have more favourable nutrient balances than overall district averages in Ghana, Mali and Kenya (FAO 2004a)

Table 15.1. District- and field-level nutrient balances for selected areas and cash crops in Africa (FAO, 2004)

Location and crop	N	P	K
	--- kg ha^{-1}	yr^{-1} ---	
Ghana, Nkawie district	-18	-2	-20
cocoa fields	-3	0	-9
Ghana, Wassa Amenfi district	-4	-1	-11
cocoa fields	-2	0	-9
Kenya, Embu district	-96	-15	-33
coffee fields	-39	-8	-7
tea fields	-16	-1	-2
Mali, Koutiala region	-12	1	-7
cotton fields	-14	12	17

Organic matter decline. The problem facing farmers in SSA is that their soils cannot supply the quantities of N required and levels of N decline rapidly once cropping commences. Most available N is supplied by soil organic matter. Organic matter levels of agricultural land are very often below those of natural ecosystems, as the rapidly decomposed part of the organic matter disappears quickly upon the removal of vegetation (Woomer *et al.* 1994). In the absence of inputs, organic matter levels drop to below 50% of the original values within a few years. Depletion of organic matter is approximately 4% per year, resulting in dangerously low organic carbon levels after 15 to 20 years of cultivation (Sanginga *et al.* 2001b). At levels below 0.5% carbon, the soil supplies less than 50 kg N ha^{-1} and this is sufficient for only about 1 t ha^{-1} of maize grain at normal levels of N use efficiency (Carsky and Iwuafor 1995). In many cases, prevailing levels of soil organic carbon are below 0.5% thereby making it urgent to incorporate organic materials. Of the plant nutrients, N is unique in that supply and replenishment of soil capital need not entail the direct application of external inputs, but rather atmospheric reserves may be exploited through BNF. N can also be supplied to field crops through use of animal manure. In general though, combined (but substantial) applications of mineral fertilizers and manure that are targeted to crop and soil conditions are able to maintain soil organic matter at levels close to original values. This balance was realized in the Brazilian cerrado following judicious use of inputs (Lilienfein *et al.* 2003).

Acidification. Acidification occurs when land is converted from natural vegetation to crops. Mineral fertilizers may aggravate pH decline, particularly with ammonium-based fertilizers ammonium sulphate, CAN, urea and DAP. These fertilizers release H+ during the nitrification process of NH4+ to NO3-. Application of lime or dolomite can prevent and rectify this situation, as does manure. Long-term data collected by Smaling and Braun (1996) for a series of trial sites across rainfed Kenya, Bado *et al.* (1997) for western Burkina Faso, and Vanlauwe and Giller (2006) for the West African moist savanna zone also showed that pH declines under no inputs and acidifying fertilizers can reach up to one full unit in 5-10 years.

Table 15.2. Variation in soil fertility status between agro-ecological zones (Windmeijer and Andriesse, 1993) and between plots within a farm (Prudencio, 1993).

Scale of soil fertility evaluation	Organic C	Total N	pH
	----------g kg^{-1}----------		
Agro-ecozones			
Equatorial forest	24.5	1.6	5.3
Guinea savanna	11.7	1.4	5.7
Sudan savanna	3.3	0.5	6.8
Fields within a farm			
Home garden	11 - 22	0.9 - 1.8	6.7 – 8.3
Village field	0.5 - 0.9	0.5 - 0.9	5.7 – 7.0
Bush field	0.2 - 0.5	0.2 - 0.5	5.7 – 6.2

Pollution. Pollution due to fertilizer application results from leaching through the soil beyond the root zone, eventually reaching groundwater, escape into the atmosphere as volatile gases, or runoff and erosion caused by heavy rainfall. In some parts of the world, these losses are high. For example in The Netherlands, more than 500,000 tons N yr^{-1} is not utilized by plants, and adds to loading of the soil. This pollution problem is amplified as a result of the high inputs of organic manure due to massive importation of livestock feed from Asia and the Americas. This type of pollution does not occur in Africa at a large scale. Of the many farming systems for Africa described by Dixon *et al.* (2001), only irrigated and peri-urban agriculture occasionally receive excessive levels of mineral fertilizers. This is the case where commodity and fertilizer price ratios are favorable. Gaseous emissions in Africa through synthetic fertilizers are expected to be quite low, even in the decades to come (Bouwman 1997).

Diversity in agro-ecological and socio-economic conditions

Because precipitation is a major factor in soil formation and land restoration has not practiced in most of SSA, most soils show increasing levels of leaching and decreasing level of nutrient reserves in response to increasing annual rainfall. Human factors, especially the way the various soil resources are managed, also contribute to nutrient depletion (Breman *et al.* 2003). While differences in soil fertility status between different agro-ecological zones are to be expected in view of what is described above, similar levels of variability in soil fertility status exist at much smaller scales (Table 15.2). Since access to nutrient sources is limited, farmers in most of SSA have been allocating them to specific spots within their farms, thus creating large gradients in soil fertility status within a single farm (Tittonell *et al.* 2005a, 2005b). Such gradients influence ISFM in terms of fertilizer use efficiency or productivity of legumes (Vanlauwe *et al.* 2006).

Strong gradients of decreasing soil fertility are found with increasing distance from the homestead in tropical farming systems due to differential resource allocation within the farm (see Chapter 4). Nutrient use efficiency varies strongly along these gradients of soil fertility. Targeting soil-improving technologies to the more degraded soils as a means for restoration of agricultural productivity is often unsuccessful. The existence of soil fertility gradients within smallholder farms must be considered when designing ISFM strategies, aiming at an improved efficiency for the overall nutrient dynamics within the farm system. Besides variability in soil fertility status between plots within a farm or village, access to resources is also variable between members of the same community. Such differences in resource endowment often form the basis for classifying farming households in typologies. Farmer typology definitions are based on a variety of characteristics or combinations thereof, including gender, food security status, participation in markets and access to remittances and social capital. Shepherd and Soule (1998) reported that farming families with higher resource endowment had access to a wider range of ISFM options, mainly due to greater access to farm inputs and a higher capacity to assume risk.

Soil fertility gradients are affected by biophysical and socio-economic conditions, and farmers' recognize such heterogeneity. Within-farm heterogeneity may be characterized by defining field types, considering distance from the homestead and differences in resource allocation, and according to

Table 15.3. Overall variance structure for soil organic carbon and extractable P at different scales in East African smallholder farms.

Scale	Soil Organic Carbon		Extractable P	
	Variance	Percent of total variation	Variance	Percent of total variation
District	3.58	9.5	8.13	18.0
Sub location	5.41	14.3	4.43	9.8
Farm	7.36	19.5	12.57	27.8
Within farm	21.43	56.7	20.16	44.5
Overall mean (mg kg^{-1})	20.4	-	10.4	-
Within farm range (mg kg^{-1})	20.4 ± 9.3	-	10.4 ± 9.0	-

farmers' perceptions. Management practices, crop productivity, nutrient balances and soil fertility status are documented for different field types and farmers' land classes within farms. Both field typologies were in agreement, as farmers commonly classified the home fields as fertile. Despite strong differences across sub-locations, input use, food production, C and N balances and general soil fertility status varied between field types, though not always correspondingly. Farmers manage their fields according to their perceived land quality, varying the timing and intensity of management practices along soil fertility gradients. The internal heterogeneity in resource allocation also varies between farms of different social classes, according to their objectives and factor constraints. The interaction of these with the location-specific, socio-economic and biophysical factors have important implications for farming system characterization necessary to target research and development interventions addressing poor soil fertility.

Table 15.4. Farmers' assessment of the soil fertility status versus measured values of SOC and extractable P along soil fertility gradients.

		Extractable P (number of fields)			
	Farmer rating	Low	Medium	High	Total
Organic C (number of fields)	Low	378	110	22	510
	Medium	113	514	89	716
	High	19	92	222	333
	Total	510	716	333	1559

Quantification of the range of within-farm soil fertility gradients allows the identification of the major biophysical and socio-economic factors driving their generation. Crops grown on depleted soils typically respond to N and P fertilizers, but fertilizer recommendations typically cover large areas and ignore within-farm soil fertility gradients common in smallholder farms. The farm fertility gradient concept is attempting to develop site-specific recommendations for ISFM based on local soil fertility classification schemes. Within-farm soil fertility gradients are large enough to be taken into account when planning the allocation of scarce nutrient inputs at the farm level. Preliminary analyses of soil organic carbon and phosphorus variance structures (Table 15.3), confirm this phenomenon of large soil fertility variation at all levels, but particularly within farms. Variation increased with district<location<farm<within farm for SOC and location<district<farm<within farm for extractable P. These results show that soil management recommendations made at the district or higher levels will not allow farmers to manage this variability adequately. Field covariates such as distance from the homestead, number of years cultivated and number of seasons that fields have been fallowed explain this variability. Position on the landscape and distance from the homestead significantly contribute to the variability of SOC and extractable P values (Table 15.4). Farmers' recognition of soil fertility gradients belong to three classes, low, medium and high compared to measured values of SOC and extractable P in soil samples taken from those fields. Farmer perceptions are fairly agreeable with measured values (Table 15.5).

The fertility gradient concept allows the determination of agronomic and spatial efficiency gains. There is much information that can help to better target fertilizer use in an efficient, environmentally benign and profitable manner. Large strides are possible towards more efficient fertilizer application, based on the ideal N-P-K ratio in plants and not on soil tests which correlate poorly to crop nutrient uptake and yield. Fertilizer response programmes in Kenya, for example, clearly show

Table 15.5 Significance of covariates in overall variance structure of soil organic C (SOC) and available Olsen-P.

Covariate	SOC	Olsen P
	---------- p ---------	
Distance from homestead	<0.001	<0.001
Seasons of fallow	0.002	0.864
Farm size	0.710	0.545
Presence/absence of flooding	0.724	0.319
Years of cultivation	0.110	0.010
Land use	0.086	0.808
Position on landscape	<0.001	<0.001

where N or P fertilizer is the proper mineral input, and where a combination of both is needed (Table 15.6). Similarly, in many West-African villages with their typical ring-based agricultural architecture, fertilizers applied in the home fields address conditions that are markedly different from those in bush fields (Table 15.7). A sound strategy is to steadily expand the home fields, releasing pressure on bush fields and maintaining mosaic landscapes and natural vegetation intensively-managed croplands.

Table 15.6. Maize yields and nutrient uptake on three soils in Kenya during the long rainy season of 1987 as affected by fertilizer application (after Smaling and Janssen, 1993).

Location and management	Maize yield	Nutrient uptake N	P	K
	------------------	kg ha^{-1}	-------------------	
Kisii Red Soils				
N 0 – P 0	2100	42	5	30
N 0 – P 22	4900	79	12	58
Homa Bay Black Soils				
N 0 – P 0	4500	63	24	95
N 50 – P 0	6300	109	35	126
Kwale Brown Sands				
N 0 – P 0	2600	38	7	42
N 50 – P 22	3700	66	16	77

Targeting technologies

During the 1990s, much emphasis was placed on the identification of best-bet technologies for different regions and target groups, recognising that technologies had too often been presented as widely applicable silver bullet solutions (Waddington *et al.* 1998). These technologies then comprise baskets of options that are recommended for testing and implementation by development workers and farmers (Mukhwana and Musioka 2003). Agro-ecological regions were considered as fairly homogenous units that could be useful as recommendation domains. When these best-bet technologies for improving soil fertility were subjected to widespread testing, they frequently failed (Woomer 2007). Among the reasons for the disappointing results was the farmers' choice of fields for technology testing because farmers often allocated their most degraded or weed-infested soils for the trials. Essentially, the soil fertility was too poor for many technologies to provide immediate benefits, or in some cases to perform over time. Severe soil degradation led to such strong soil fertility constraints that the legumes produced insufficient biomass to result in land restoration.

Substantial emphasis has been placed on understanding the local heterogeneity in farming systems and soil productivity across regions, landscapes, within farming systems and within and between farms (Giller *et al.* 2006; Vanlauwe *et al.* 2006). Within any given country or region there are also more localized agro-ecological gradients, and large differences between regions in terms of access to markets. Within every village, a wide diversity of farming livelihoods can be found, differing in production objectives and in wealth and resource endowments (Tittonell *et al.* 2005a; Zingore *et al.* 2007a). Past management by farmers strongly affects current soil fertility. Across distances of only 50-100 m the range in soil C contents can be as large as that across a whole region (Tittonell *et al.* 2005b; Zingore *et al.* 2007a). These differences in soil fertility are due to the repeated preferential allocation of organic residues and fertilizers to favored fields, commonly those closest to the homesteads. Gradients of decreasing soil fertility with distance from the homestead can be created within only a few years of such expedient management of the close fields and cropping of outfields

Table 15.7. N stocks (0-15 cm), N uptake and millet yield, as a function of distance from the homestead in the Bankass Area, Mali (after Samaké, 2003)

Distance from compound meters	N stocks	N uptake	millet grain yield	
	--no fertilizer applied--			----+N+P[1]----
	---------------------	kg ha^{-1}	---------------------	
10-200	600	24	1130	1730
500-2000	300	14	480	1020

[1] 38 kg N and 20 kg P ha^{-1} applied

without inputs. Furthermore, the resource endowment of the farmers determines the strength of these gradients. Wealthier farmers, who have substantial numbers of cattle and manure, and adequate labor, tend not to have strong gradients of soil fertility across their farms. The poorest farmers also tend to have fairly uniform poor fertility across their fields, as they have little access to animal manure or other organic residues and often little labor available for investment on their farms. The intermediate groups of farmers, who are generally by far the greatest proportion in any given area, tend to have stronger gradients across their fields due to the preferential allocation of limited organic manures to the fields closest to their homesteads (see Table 17.1).

The existence of these local soil fertility gradients explains most of the variability in performance of the best-bet technologies. The legume-based technologies for soil fertility enhancement often perform poorly in degraded outfields. The soil condition strongly influences the efficiency with which mineral fertilizers are used by crops. On sandy granitic soils, nitrogen use efficiency by maize varied from >50 kg grain kg^{-1} N on the infields, to less than 5 kg grain kg^{-1} N on the outfields (Zingore *et al.* 2007b). Ojiem *et al.* (2006) derived the concept of the 'socio-ecological niche' for targeting technologies, taking cognizance of the need to recognize heterogeneity among and within farms. The appropriateness of technologies is determined by both agro-ecological factors and socioeconomic factors (Figure 15.2). A technology works best when embedded into the local social, economic and agro-ecological conditions.

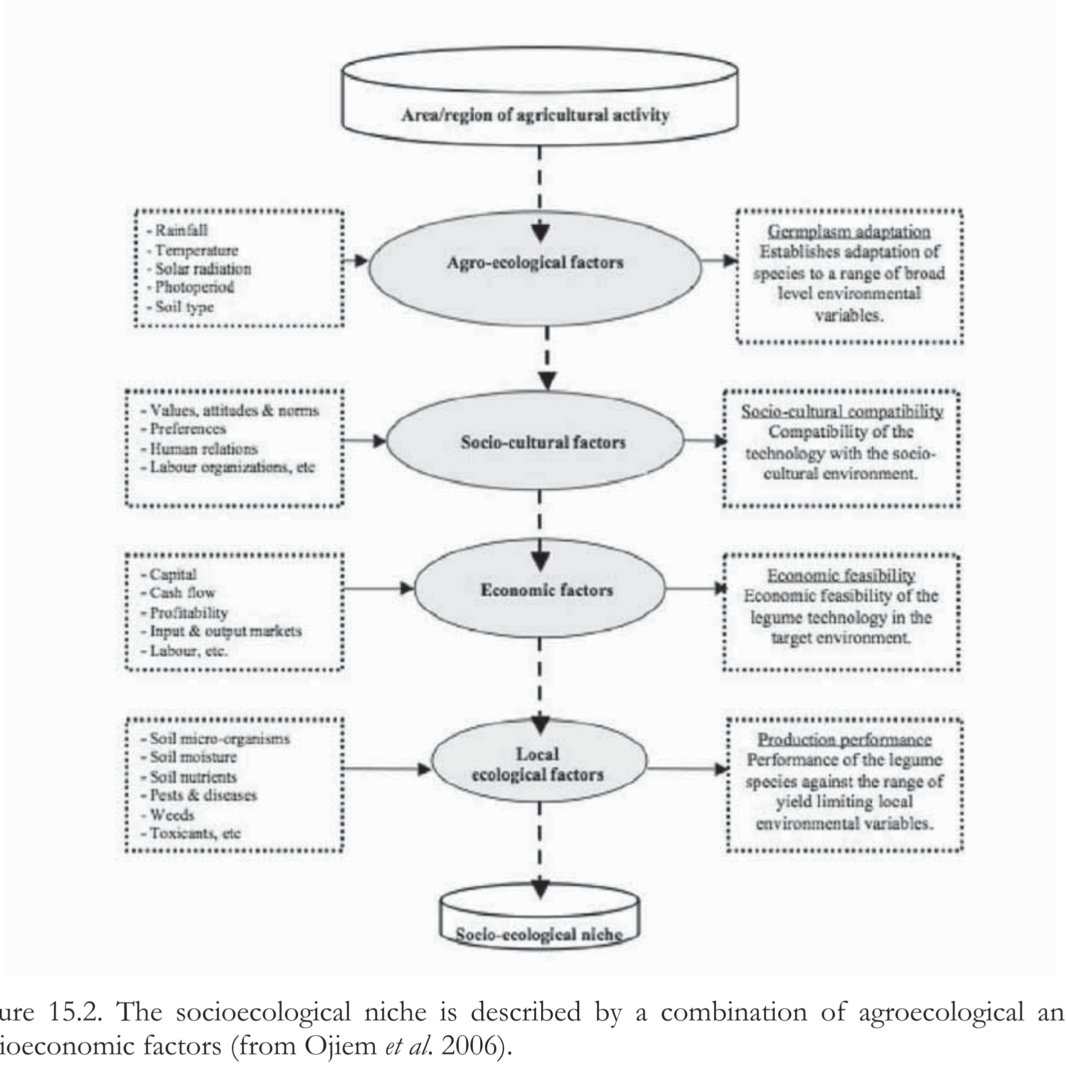

Figure 15.2. The socioecological niche is described by a combination of agroecological and socioeconomic factors (from Ojiem *et al.* 2006).

Evidence-based diagnostic surveillance of soil degradation.

There is little doubt that the soil fertility problem in Africa is severe and widespread, but the data on which this diagnosis is based are deficient. Current knowledge on fertilizers and the environment is poorly reflected in legal frameworks and in extension messages. There is a general absence of a monitoring and evaluation mechanisms within environmental reporting systems, and of strategies that link resource quality and dynamics to future targets in agriculture, livestock development and forestry. The combination of laborious methods and a shortage of scientific and technical expertise have meant that diagnostic analysis has been limited geographically and has rarely been repeated. Continuation of the past diagnostic approach is too slow to secure sustainable soil management for the continent but methods now exist for rapid and repetitive analysis on a continental scale. The application of a diagnostic surveillance system based on approaches used in the public health sector is needed to rapidly provide soils information targeting intervention actions, and serve on a wider scale as the basis for policy action and dissemination. Soil health surveillance is the ongoing systematic collection, analysis and interpretation of data essential to planning, implementation, and evaluation of soil management policy and practice, which is closely integrated with the timely dissemination and application of data that is used for prevention and control of soil degradation. Soils are healthy when they are capable of supporting ecosystem services on a sustained basis (Millennium Ecosystem Assessment 2005). The approach employs the latest scientific and technological advances including remote sensing and GIS, infrared spectroscopy for rapid soil analysis and new multivariate statistical tools for analyzing hierarchical spatial data (Shepherd and Walsh 2007). This diagnostic approach (Box 15.1) provides a vastly improved African soil database forming the basis for targeting intervention and policy actions.

Soil health surveillance provides a coherent, spatial framework for ISFM diagnosis, testing and impact assessment. Case definitions for specified problems are defined, such as what constitutes strong soil acidity and screening tests developed to rapidly diagnose samples as affected and non-affected. Infrared spectroscopy is applied as a rapid screening tool for soil and plant analysis. Infrared spectroscopy may prove to be one of the most cost-effective and reproducible analytical techniques available for the 21st Century and is already a standard analytical technique in the food and fodder industries (FAO/IIASA 2002). It has been shown to be widely applicable in African soils and for characterization of tropical organic resources

Box 15.1. A diagnostic surveillance system for soil-based constraints to African agriculture

- A diagnostic surveillance approach to soil-related problems is used to achieve three objectives: to provide diagnostic information for resource allocation; to identify cause-and-effect relationships for prevention, early detection and rehabilitation; and to monitor outcomes and impact of soil management interventions.
- Surveillance procedures developed in the public health sector serve as a model. Components include problem definition; case definitions; screening tests; baseline surveys that measure environmental interactions to quantify risk factors; and confirmation of risk factors using incidence monitoring. Soil degradation prevalence surveys collect information on soil and vegetation conditions and trends, land use management, and socioeconomic conditions.
- The causes of soil degradation are identified at different scales so that results can be linked to a region with known levels of confidence. Random sampling is used to provide unbiased estimates on soil constraints and degradation.
- The approach builds databases for spatially explicit scenario analysis, the design of large-area management and policy interventions, and the prioritization of resources at different scales.
- The approach provides a spatial framework for research and demonstration trials that systematically sample the ecological and socioeconomic variability in an area. This in turn provides predictive understanding of factors affecting intervention performance across a range of conditions in the target area.
- The approach identifies control areas for assessing intervention impacts of development projects. In addition, impacts of specific interventions are monitored using replicated 'Before-After-Control-Impact-Pair' designs, to act as a control for spatial and temporal confounding effects.

(Shepherd and Walsh 2007). This non-chemical approach requires little sample preparation and covers many applications with the same instrument, having obvious advantages for developing countries. Low cost and high-throughput methods make large-scale area diagnostic surveys more feasible.

The approach avoids the need for conducting soil testing on every farmer's field, and instead relies on establishing average values of soil fertility variables for the population of farmers' fields in a locality, country or region based upon a nested sampling schemes and then builds empirical statistical models to quantify how management and edaphic factors cause deviation of fields from the average. The understanding generated from this analysis is then used to both guide policy at higher levels of scale, and provide farmers in a given locality with relevant information for managing their soil constraints. Diagnostic surveillance approaches can make field testing and demonstration programs enormously efficient. Sentinel sites of 100 km^2 established during diagnostic surveys provide a hierarchical spatial framework for establishing field trials so that results can be generalized. The sentinel sites also provide spatially explicit baseline information for impact assessment.

An additional benefit of national soil health surveillance systems is that monitoring of environmental correlates is built into the system, providing ability to examine key impacts within the same framework. These include variables such as vegetation type, ground cover and field-measured infiltration rates serving as proxy indicators for soil erosion risk, especially in relation to erodible soil types and steep slopes. Woody vegetation cover is a proxy indicator for wind erosion risk on susceptible soils in dry areas and for nutrient leaching risk in humid areas. Soil degradation in close proximity to waterways is an indicator of stream bank erosion and sedimentation. More detailed studies imposed on the sentinel site sampling scheme also provide ability to calibrate direct measures of environmental problems to readily measurable soil and vegetation attributes. A regional program could provide the needed scientific and technical advisory and analytical services in soil health surveillance while long-term national capacity is being established. For example, implementing field survey and experimental programs does not need a high degree of specialization whereas survey and experimental design, data handling, and statistical analysis and interpretation do. Internet-based data entry systems and centralized statistical analysis is a viable means of collecting and disseminating this information.