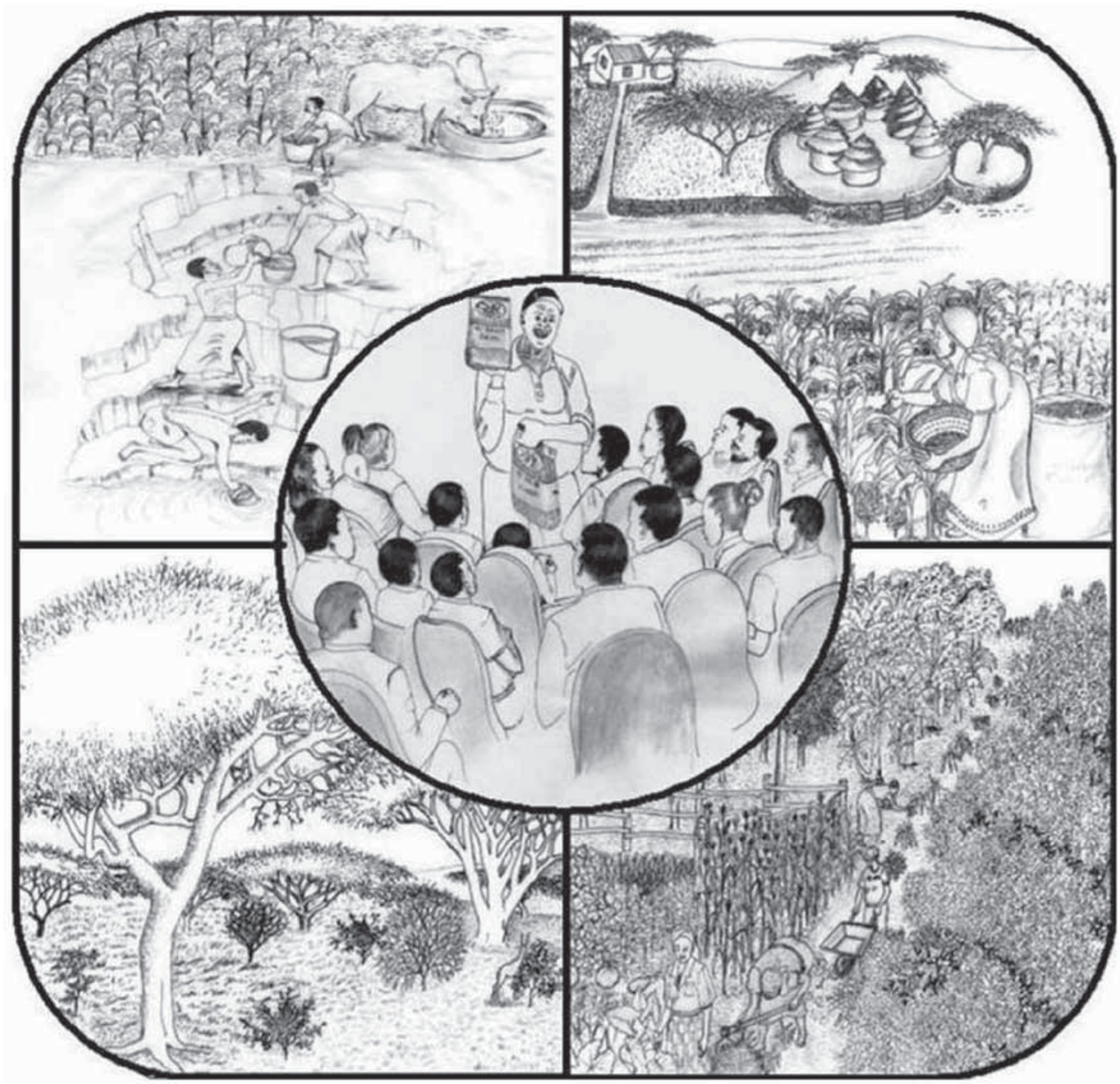
Part II.

ISFM Practice



Chapter 6. ISFM products and field practices

Several features distinguish ISFM from past, more conventional field practice. ISFM involves more than just periodic addition of mineral or organic nutrients to soil. Rather it requires a year-round suite of field activities designed to optimize nutrient acquisition, delivery and recycling. These field practices are not merely built upon the use of purchased farm inputs alone, but rather involve the systematic collection and processing of farmer-available organic resources and the optimization of beneficial biological processes. ISFM practices are not rigid, but rather based upon principles, site-specific conditions and farm enterprises. In this way, ISFM advice represents a suite of informed options that can vary with and between crops, seasons and landscape positions rather than the result of a top-down recommendation process.

Another distinctive feature of ISFM is the manner in which it combines land management field practices with farm input products. Fertilizers and their various forms and formulations are the most important of these products, but by no means the only ones (Table 6.1). Fertilizer forms range from single granular types and their blends, to compound (combined), and complete kinds designed to provide balanced combinations of nutrients needed by specific crops. Compound fertilizers may be encapsulated within osmotic membranes to control their release characteristics. Specialized fertilizers are also available as sources of micronutrients or that provide feeding through leaves as foliar fertilizers. The use of these mineral fertilizers is not intended as a standalone soil fertility management practice however because the effectiveness of fertilizer use and its partial replacement is greatly influenced by interactions with organic inputs. Agro-minerals are also commercially available for use as soil amendments and nutrient sources. Most notably these include agricultural lime to raise soil pH, sulfur to lower pH and rock phosphates (van Straaten 2002). Other mineral soil amendments include pumice and vermiculite but these materials are more often applied to potting mixtures and seedling beds than to field soils.

While organic inputs are sometimes marketed by farm input suppliers as compost, guano, manure and other nutrient-rich materials, they are more efficiently stockpiled, processed and applied as organic resources available within and beyond the farm. Animal by-products offered for sale include blood and bone meal but these are more often used to biofortify animal diets than to improve soils. Numerous agro-industrial wastes are not included within Table 6.1 such as coffee husks, sugar cane bagasse and coconut fiber but are described within Chapter 4. Those materials that cannot serve as livestock feed tend to be quite inexpensive or free but their bulk and transportation cost tends to limit their usefulness as distance from their source increases.

Other farm input products address soil moisture deficits including sprayed anti-transpirants that restrict leaf stomata and hydrogels that greatly increase soil water storage. Herbicides with either broad or specific activities against unwanted plants are available for use in reduced tillage systems and in controlling weedy invasion. Legume inoculants are applied to seed before planting to ensure that the proper symbiotic rhizobial bacteria are present for root nodulation and biological nitrogen fixation. Other inoculants containing symbiotic mycorrhizal fungi, rhizosphere organisms and biological catalysts are also available but have irregular or unproven benefits. Inoculant organisms that are potentially beneficial to crops are very often rapidly out-competed by more saprophytically competent indigenous microorganisms (Lowendorf 1980).

This discussion is not intended to suggest that the more diverse range of products that are purchased and applied to soils and crops will necessarily result in healthier soils and larger yields, but rather to reinforce that numerous merchandise, some widely available and others more specialized, can backstop more refined efforts at ISFM. In fact, care must be taken when evaluating new soil fertility management products because advertisement claims are sometimes exaggerated or based upon limited evidence. As a result, many of their effects are best described as mixed (Table 6.1). One class of farm product that warrants further distribution is diagnostic apparatus and kits that characterize soil acidity, moisture and nutrient status. Perhaps extension

Product	Role	Cost	Availability	Effect
Agricultural lime	Increase soil pH	low	medium	high
Anti-transpirant	Reduce crop moisture loss	high	low	mixed
Blended fertilizer	Adjust nutrient ratios	medium	medium	high
Blood meal	Organic source of N	medium	low	mixed
Boneimeal	Ca and P source	medium	medium	medium
Broad spectrum herbicide	Destroy all weeds	high	medium	high
Broadleaf herbicide	Destroy dicot weeds in cereals	high	medium	medium
Compost	Provide organic nutrients	low	mixed	high
Compound fertilizers	Combine fertilizer sources	medium	medium	high
Complete fertilizer	Apply all nutrients	high	low	high
Elemental sulfur	Lower soil pH	low	low	mixed
Free-living N-fixers	Improve plant nutrition	medium	low	mixed
Foliar fertilizers	Correct nutrient deficiencies	high	mixed	high
Granulated fertilizer	Simple fertilizer source	high	medium	high
Guano	Provides organic N&P	medium	low	medium
Hydrogel	Improves moisture holding	high	low	mixed
Legume inoculants	Improve legume BNF	medium	low	mixed
Microbial catalysts	Stimulate microbial activity	high	low	mixed
Microbial control agent	Protect plants against pathogens	medium	low	medium
Micronutrient fertilizer	Correct micronutrient deficiency	high	low	mixed
Monocot herbicide	Destroy grasses in broadleaves	high	medium	mixed
Moisture meters	Quantify soil moisture	high	low	diagnostic
Mycorrhizal inoculant	Improve root performance	high	low	mixed
Nitrogen fertilizers	Provide mineral N	medium	medium	high
P-solubilize organisms	Solubilize phosphorous	low	low	mixed
Pelleted fertilizers	Synchronize nutrient release	medium	medium	high
pH meters	Measure soil acidity	high	low	diagnostic
Plant Growth Regulator	Stimulate plant root growth	medium	low	mixed
Potting mixture	Media for container plants	low	low	mixed
Pumice	Aerate soil, improve drainage	low	low	mixed
Rhizobial inoculant	Improve legume BNF	medium	low	mixed
Rock phosphate	Provide P and other nutrients	low	low	mixed
Vermiculite	Improve water holding, K source	low	low	mixed

staff rather than individual small-scale farmers best use them but the information they provide can assist in refining their approaches to land management.

Let the buyer beware

Technological breakthroughs in soil fertility are rare, but there are notable exceptions. Some products, such as rhizobial and mycorrhizal inoculants have been proven to substantially enhance the productivity of specific crops (Giller 2001). However, there is also a proliferation of new chemical and biological products appearing on the market that claim major impact in increasing crop productivity. Many of the latter claim to bring benefits across a wide range of crops, including cereals, grain legumes, root crops, vegetables and fruit trees, and to substantially improve both yield and produce quality. These commercial products usually display their efficacy through visual observations and photographs, and rigorous, in-depth scientific evaluation of these products that confirms their claims is too often lacking. The exact processes and mechanisms underlying product claims and the conditions under which these may occur are seldom explained in product information and often protected as trade secrets.

These products demand rigorous testing to verify whether they can fulfill the claims of the manufacturer. Such testing needs to be conducted by an independent third party with no vested interest in the outcome of the evaluation. The proliferation of under-performing products must be prevented, so that effective new products capturing technological breakthroughs do not become lost among a pack bogus merchandize. The value and efficacy of new products can be established by directly comparing and integrating them within other proven soil fertility management practices. Technologies that have a scientific basis also require further validation in order to identify the necessary context in which they perform best. The evaluation of numerous commercial agricultural products and seed technologies requires rigorous scientific appraisal under controlled growth conditions, and the more promising ones then examined in the field under a representative range of conditions and management practices.

To conduct such product screening, a tier-structured, funnel approach is employed. Initially, large numbers of product samples are evaluated in pots or small plots with a focus upon performance under defined conditions. At later stages, samples will be narrowed to a few products evaluated collaboratively with farmers under differing soil conditions, cropping systems and environmental factors. The stepwise components of phased testing are 1) laboratory characterization, 2) bio-assays under greenhouse conditions, 3) researcher designed and managed field trials, 4) multi-locational on-farm trials testing promising interventions within ISFM technologies, and 5) widespread on-farm adoption trials. Only products that pass the quality criteria and prove to be effective are taken to the next step of testing. Products that fail the criteria at a given step are discarded, or if need be, specific testing can be conducted to understand conditions under which the product is least and most effective before taking it to the next step of the authentication process.

Product testing is not always straightforward because of the scope of advertised benefits, but extremely important to check excessive claims. One new product contains three "compatible, naturally-occurring microorganisms" that are claimed to induce root secretions, excrete plant growth substances, stimulate mycorrhizal activity, suppress plant pathogens, accelerate decomposition and promote plant cell division (Chandi 2003). The product is intended for dilution at rates from 1:100 to 1:1000 for application to soils, plants and composts. The product claims to increase tomato yields over 10-fold without the addition of mineral fertilizer or manure. It also claims to repel insects and serve as a livestock feed supplement, and even to treat human disease. This product was originally developed in Japan, now is produced in vat culture in East Africa and is appearing on the shelves of many farm input suppliers. If such a product meets its claims it can prove a boon for farmers, but if not it only serves to confuse and frustrate them.

A sound knowledge of the conditions governing product efficacy is a crucial criterion for advancing products into widespread use. At the same time, it is acknowledged that sufficient scientific evidence is already available for several of these products. Rhizobial inoculants have a very high chance of success and, after the identification of promising strains, these inoculants can advance quickly through authentication. Seed coating with pesticides and starter nutrients also has a high probability of success. Partnerships and linkages with local stakeholders and service providers provide the means to quickly share the best technologies and methods to wider areas. Scientific publications describing effective and questionable products are helpful, but require simplification to become a full asset to a broader dissemination strategy as the scaling up process requires production of stakeholder-specific and user-friendly dissemination tools (see Chapter 13).

The central role of legumes in ISFM

One ominous trend that argues for greater importance of legumes within African ISFM is the sharp increase in fertilizer prices. Until recently, increased fertilizer use was viewed as the central feature in reversing land degradation and achieving food security, as described by the African Fertilizer Summit (2006). Since then, fertilizer prices have skyrocketed by about 130%, largely due to increasing costs of petroleum. Commodity costs have also increased but not nearly kept pace resulting in very different profitability of fertilizer use compared to recommendations

Table 6.2. Changing fertilizer prices may require re-evaluation fertilizer recommendations (after Woomer 2007).

Growing season and management recommendation	2004 costs and prices: production costs: fertilizer (KSh ha^{-1})	total (KSh ha^{-1})	net return (KSh ha^{-1})	benefit: cost ratio	2008 costs and prices: production costs: fertilizer (KSh ha^{-1})	Total (KSh ha^{-1})	net return (KSh ha^{-1})	benefit: cost ratio
Long rains season								
FURP recommendation[1]	7200	20819	38422	2.85	18600	32219	27022	1.84
ISFM with MBILI [2]	4600	19537	51779	3.65	11800	26737	44579	2.67
Nutrient replenishment[3]	3920	17427	36538	3.10	13840	27347	26618	1.97
Short rains season								
FURP recommendation	4000	16706	22179	2.33	10400	23106	15779	1.68
ISFM with MBILI	1400	15436	32924	3.13	3600	17636	30724	2.74
Nutrient replenishment	3920	16808	22856	2.36	8720	21608	18056	1.84

[1] FURP recommends 66 kg N and 20 kg P_2O_5 during the long rains and 26 kg N during the short rains. [2] MBILI receives 31 kg N and 20 kg P_2O_5 in the long rains and 13 kg N in the short rains. [3] Nutrient replenishment applies a onetime application of 800 kg Minjingu Rock Phosphate (100 kg P_2O_5) and 35 kg N each growing season that follows.

formulated only a few years ago. An example from West Kenya compares three different fertility management recommendations (Table 6.2); one from the KARI-FURP Program, another from ISFM "Best Bet" field trials and the last derived from nutrient replenishment approaches (Woomer 2007). Simply stated, fertilizer practices that were profitable in 2004 are much less so in 2008. Whereas any of these recommendations could be justified in 2004, only the ISFM MBILI package offers acceptable returns under 2008 fertilizer and commodity prices. The MBILI technology relies upon nitrogen fixing grain legumes, providing them competitive advantages within the maize understorey and in turn, the following maize benefits more from their legume residues (Woomer *et al.* 1997).

Participation in legume enterprises by small-scale farmers has numerous benefits, both direct and indirect. Many field legumes produce high yielding grains that greatly improve household diets. These field legumes are readily marketed at prices greater than cereal or root crops. Legumes provide livestock feed and their crop residues offer benefits to soil through biological nitrogen fixation that, in turn reduce the requirement for costly mineral fertilizers. A small-scale farming household that has incorporated legumes into its enterprises is in a better position to raise its wellbeing and to meet expectations in improved living standards.

The opportunities in achieving the potential of legumes within these farms are complex and inter-related (Figure 6.1). Legumes offer stress tolerance in terms of climate and extreme soil conditions but are often susceptible to pests and disease. Symbiotic BNF allows many legumes to meet their nitrogen requirements from the atmosphere rather than the soil but effective nodulation may be inhibited by the resident population of rhizobia. In many cases, realizing legume potential has required that needed traits be reinforced through crop selection and breeding. For the first time, agriculturalists have access to promiscuously nodulating indeterminate soybean (*Glycine max*), virus resistant groundnuts (*Arachis hypogeae*), rust resistant grams (*Vigna aureus*) and lablab (*Lablab purpureus*), root-rot resistant and acid tolerant beans (*Phaseolus vulgaris*) and other improved grain legume traits. The challenge remains, however, to make these improved legumes more readily available to farmers.

Small-scale cereal farmers have two basic options to increase their grain legume enterprise, either producing pulses as an intercrop or in rotation with cereals. Maize-bean intercropping is a widespread practice in Africa but within this cropping combination farmers' expectations are seldom achieved (Table 6.3), in large part because of the poor performance of this legume intercrop. To some extent, farmers' dependence upon bean results from lack of accessible alternatives. This is the case also for cowpea and cereal intercropping in West Africa. One of the main goals of ISFM is to diversify grain legume enterprise by making improved varieties more

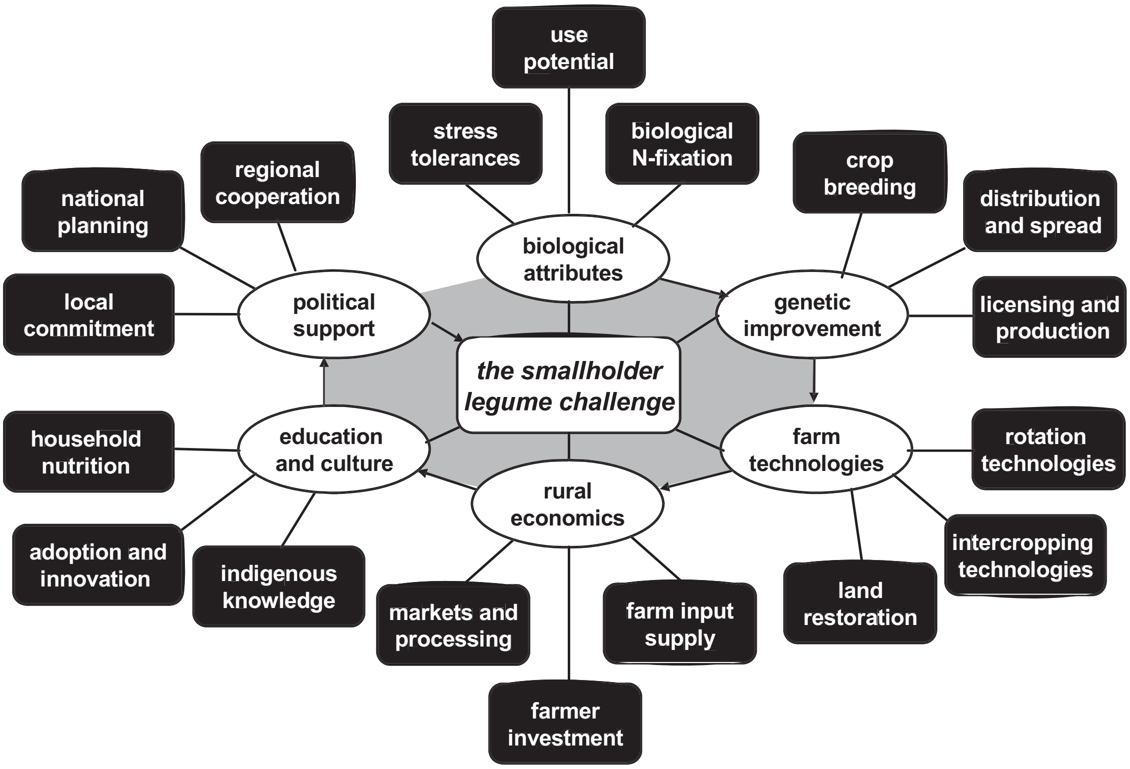


Figure 6.1. The challenge of increasing legume enterprises within small-scale farms in Africa has several key aspects relating to biology, crop genetic improvement, useful technologies, rural economic, cultural perspectives and political support.

available to farmers within the context of improved of household nutrition, income generation and land quality improvement.

Another legume-based technology is land restoration where cover crops are established and soils are stabilized and improved over time (Ojiem 2006). From our perspective, only severely eroded, physically degraded and abandoned soils require this management because treated land is placed out of production for extended intervals. A related technology, green manures, offers similar regenerative services but is difficult to manage from a labor perspective. In general, grain legumes are not well suited as cover crops or green manures as a different suite of plant characteristics are required with the notable exception of lablab (*Lablab purpureus*) that provides both vegetative cover and edible seeds (Duke 1981).

Rapid adoption of legume-based ISFM requires availability of farm inputs, farmer investment in those inputs and that crop surpluses resulting from improved farming are readily marketed (Crawford *et al.* 2003; Bingen *et al.* 2003). Innovation in input supply is necessary. Fertilizers not

Table 6.3. Advantages and disadvantages of bean (*Phaseolus vulgaris*) as a smallholder's intercrop with maize

Advantages	Disadvantages
Farmer's own seed may be planted	Susceptible to foliar & root diseases
Quick germination & establishment	Attacked by numerous pests
Shade tolerant understorey growth	Specific requirement for nodulation
Edible leaves, green pods and seed	Low potential for symbiotic N-fixation
Fast maturing	Difficult to weed
Fast cooking & preferred taste	Very low grain yields
Good price & strong markets	Crop residues of little value

containing nitrogen (e.g. P, K. S) and agro-minerals such as rock phosphate and limestone can greatly benefit legumes in low fertility soils. These inputs are available throughout SSA (see Chapter 3) but not widely marketed by rural stockists. Commercial producers are marketing some improved legume seeds and demand for these products must be stimulated. In some cases, grain legumes require inoculation with rhizobia to achieve their symbiotic potential (Giller 2001). In this way, grain legume enterprise is based upon a unique suite of farm inputs and means must be found to mobilize and popularize these products.

Indeed, farmers must be provided incentives to invest in these ISFM technologies, whether through better marketing, wider extension of credit, and application of smart subsidies or the distribution of introductory soil fertility management packages. To a significant extent, the adoption of improved grain legumes has stalled because seeds are unavailable and means must be found to secure certified seed for community-based seed production. Grain legume commodity markets are not well organized, particularly for grains with industrial applications such as milling and oil extraction. Farmer associations that participate in legume-based ISFM programs must also embark upon collective marketing. Retailers that sell ISFM inputs can also serve as produce collection points for grain quality assessment and bulking. Food processing companies that routinely import grain legumes must be encouraged to reduce their minimum orders to accommodate local producers entering the market.

Not all of the adoption of new crops is driven by market opportunities however because education and culture play a strong role in farm planning. Many farmers are unaware of the beneficial interactions between cereals and legumes. Even root nodulation by legumes is not well understood (Woomer *et al.* 1997). Farmers lack the information and experience necessary to adapt grain legumes within specific farming conditions. Finally, households are unfamiliar with the dietary advantages of grain legumes and how to best utilize them (Graham and Welch 1999). In some cases, gender roles within farms dictates who cultivates them, how much may be invested and who benefits from their sale (Ashby *et al.* 2008). For these reasons, information campaigns occupy an even more important role within ISFM and legume enterprise adoption among poorer, more traditional households.

Several constraints restrict legume-based ISFM expansion in Africa (Figure 6.1). Availability of fertilizer composed of the major limiting nutrients for a specific area and local knowledge on how to best apply these are often lacking. Availability of quality seeds is reduced because seed companies consider legume seed production to be less profitable than cereals, particularly hybrid maize. Poor agronomic practices are a common factor in the region's farming systems, which leads to low yields of grain legumes. This malpractice includes coarse seed bed preparation, untimely planting, poor spacing, incorrect nutrient application, incomplete weed control, uncontrolled diseases and pests, incorrect harvest schedules and poor post-harvest handling. Lack of knowledge on local processing, utilization and nutritional benefit is also a hindrance to enhanced production. Disorganized legume value chains result in large inefficiencies and higher producer prices. Ironically, some countries import large quantities of legumes, particularly soybean, for use in protein fortification of food and animal feeds yet farmers entering into soybean production are unable to market their surpluses. Lastly, front–line extension agents too often have incomplete knowledge of grain legume and fertilizer management and may spread misinformation about them.

Political support at the local, national and regional levels is necessary for the accelerated adoption of ISFM (Figure 6.1). The allocation of limited front-line extension expertise poses a dilemma for local supervisors. Community leaders and farm organizations voicing demand for ISFM services can, however, attract resources and commitment in their direction. An even greater impact is felt at the local level when the officers of successful farm organizations are invited to serve on local development committees or are viewed as assets by local policymakers.

National policies have an obvious role in promoting ISFM. National planners can increase the resources devoted to agricultural development and natural resource management. Extension agents may be retrained, educational curricula revised, smart subsidies and tax incentives offered, investment in farm input supply stimulated, vouchers for farm inputs issued, and integrated community schemes may be launched. One thing is for certain, however, there are insufficient funds for everything that is needed at once and policymakers must be provided the facts necessary for realistic priority setting (see Chapter 19).

Another missing ingredient in policy support is regional cooperation. It is sad to see that even after signing numerous trade agreements, improved crop varieties, farm input supplies and agricultural commodities do not flow freely across national borders. National agencies too often refuse to acknowledge the registration of farm input products by their neighbors and force suppliers to repeat tedious application procedures. Some food processors issue forward contracts that specifically exclude produce from neighboring countries. Improvement has resulted from assigning duty-free status to farm inputs, but this has yet to untangle the congestion of supply lines crossing national borders. Clearly, it is past time that regional cooperation extend beyond expressions of good will and instead offer tangible opportunities to small-scale farmers ready to update their soil management and crop production practices. The issues raised in this sub-section clearly demonstrate that the expansion of legume-based ISFM requires more than willing farmers, but also a scientific, economic, educational and policy environment that facilitates better understanding of agricultural resources, the mobilization of those resources, incentives for input suppliers and farmers and a marketing and policy environment that favors progress above the status quo.

ISFM field practices

In several ways, ISFM does not differ radically from more conventional management. Pre-plant fertilizers are applied, but their use efficiency is enhanced through combination with organic inputs. Pre-plant fertilizer applied to symbiotic legumes does not include excessive nitrogen, but rather contains other nutrients that are required in greater amounts by nitrogen-fixing systems. Rhizobial inoculants are applied to legume seeds when the native population cannot enter into effective nodulation and symbiosis (see Chapter 5). Nitrogen top-dressing is applied to cereals and vegetables as split applications that are timed to weeding operations or moisture availability. In addition, more strategic nitrogen top-dressing permits use of lower cost, more concentrated forms of fertilizer, such as urea. No nitrogen top-dressing is required by symbiotic legumes and rather should be directed toward cereal intercrops and other crop enterprises.

One approach to ISFM involves the development and promotion of practical land management options among small-scale farmers (Table 6.4). The four basic approaches to better soil fertility interventions involve 1) strategic fertilizer application, 2) increasing biological nitrogen fixation, 3) improving nutrient recycling and 4) strengthening crop-livestock interactions (Woomer *et al.* 1999). Strategic fertilizer application includes alternative approaches where nutrients may be replaced on a regular whole-field basis (Mokwunye *et al.* 1996), applied in small amounts to individual plants (Tabo *et al.* 2006), replenished in large amounts following long-term depletion (Sanchez *et al.* 1997) or applied to emerging nutrient-deficient patches as they express themselves (Okalebo *et al.* 2006). The nutrient use efficiency of each of these approaches may be improved through combination of mineral fertilizers with organic inputs (Palm *et al.* 1997). Nitrogen fixation may be enhanced through the production of grain legumes that are inoculated with rhizobia as required (Giller and Wilson 1991, Woomer *et al.* 1997), cultivating leguminous cover crops and green manures, and by planting field and farm boundaries in N-fixing shrubs and trees. Specific field practices that increase nutrient recycling and reduces nutrient loss include establishing trash lines of coarse plant residues along the soil contour at regular intervals, recovering plant biomass from field, farm and community boundaries, and re-vegetating degraded lands with cover crops, shrubs and trees. Livestock-crop interactions may be strengthened through increasing the size and quality of livestock and improving their diets, improving the recovery of manures by confining livestock, adjusting the handling and storage of manures and composts (Lekasi *et al.* 1998, Ndungu *et al.* 2003), and conducting stubble and tether grazing in croplands between seasons (Powell and Williams 1995). All together, this menu comprises 18 practical options for small-scale farmers (Table 6.4), each with its own advantages and facilitating conditions. This list is by no means exhaustive but rather intended to illustrate the range of useful field practices available to farmers. Other practices specific to different agro-ecological zones are presented in the following Chapters.

ISFM in a monomodal rainfall regime. Even the simplest of ISFM applications within a single cropping cycle per year may require that several key field practices be undertaken at different stages of the growing season. Take for example a sub-humid monomodal rainfall regime suitable for a maize-legume intercrop (Figure 6.2). Land preparation includes tillage and the establishment of contour furrows and pre-plant fertilizers are incorporated. The furrows may be connected through tied ridges to reduce water runoff early in the season. The maize-legume intercrop is planted during the first wet month followed by weeding, nitrogen top-dressing and a second weeding. If urea is applied as a top dressing, it is important to combine it with weeding operations, permitting shallow incorporation and reduced loss from volatilization of ammonia. The understorey legume intercrop generally reaches harvest maturity several weeks before maize. Up to this point, there is little to distinguish this cropping system from conventional modern agriculture.

More integrated approaches to soil fertility management are achieved through the management of crop residues and the establishment of a relay green manure. First, the legume stover recovered during harvest is spread. Then a drought tolerant, trailing green manure such as lablab or mucuna is planted beneath the maize, taking advantage of the last two wet months. The seedlings establish in near-complete shade but as the maize matures, more light penetrates to the

Table 6.4. Specific field practices for better management of crop nutrients and the conditions that facilitate their utilization.

Category and practice	Facilitating conditions
Strategic fertilizer application	
Replace field-scale nutrient losses regularly	Pre-plant fertilizers available and marketed
Micro-dose individual plants	Fertilizers packaged into smaller quantities
Apply nitrogen top-dressing	N addition and weeding operations combined
Replenish long-term nutrient loss	Low cost agro-minerals available
Practice patch amelioration	Inputs repackaged and combined
Combine mineral and organic inputs	Organic resources recovered and processed
Increasing biological nitrogen fixation	
Practice legume intercropping or rotation	Improved grain legumes available
Inoculate legume seed with rhizobia	Inoculants understood and available
Cultivate cover crops and green manures	Sufficient land available
Establish N-fixing trees along boundaries	Land and tree tenure established
Improve nutrient recycling (reduce nutrient loss)	
Establish trash lines along contour	Coarse crop residues available, land sloped
Recover and spread biomass from boundary areas	Sufficient organic resources & labor available
Revegetate degraded and eroded areas	Plants available, community resources pooled
Promote livestock-crop interactions	
Increase herd size and quality	Sufficient carrying capacity available
Improve diet and manure quality	Investment in fodder and feed profitable
Increase efficiency of manure recovery	Confinement of livestock feasible
Improve handling & processing of composts	Labor and materials available
Stubble and tether grazing	Low risk of livestock theft

understorey. When the maize is harvested, its stover is chopped and knocked down, providing additional opportunity to the green manure. In some cases, it may be necessary to spot weed the green manure but more often it will have a strongly suppressive effect on unwanted plants. The green manure continues to grow for a few months, forming a thick layer of leaf litter. Toward the end of the dry season the legume loses its vigor, and prior to the next cropping cycle is chopped to facilitate incorporation into the soil during tillage. In this way, several tons of organic materials and large amounts of nutrients are recycled into the soil.

Relay green manures are admittedly labor intensive but offer numerous benefits in terms of crop returns, fertilizer use efficiency and soil health. In some cases, the thick litter layer complicates tillage operations and makes seedbed preparation more difficult. The litter volume may be reduced by periodic pruning for use elsewhere as mulch or fodder. Alternatively, the maize stubble and declining green manure may be grazed to further reduce and fragment litter. The green manure legume may also provide a useful grain that is harvested midway through the dry season. Specific green manure species and their management are described in further detail within Chapter 10.

ISFM in a bimodal rainfall regime. Figure 6.3 illustrates field tasks required to produce a maize-soybean rotation in a sub-humid climate with bimodal rainfall distribution. In this example, a maize-legume intercrop is produced during the more plentiful long rains, a faster maturing soybean crop is cultivated during the following short rains and crop and weed residues are recycled through livestock. Indeed, ISFM is reflected in all stages of the crop production cycle including land preparation, mineral fertilization, planting, weeding, and the management of crop residues, livestock and their manure.

Livestock may serve as the focus for the recycling of organic resources in the scenario presented in Figure 6.3. These resources include crop residues, weeds and trash remaining in the field between crop cycles. The manure resulting from consuming these materials, along with that from purchased feeds, are regularly gathered, piled and mixed with other decomposable organic

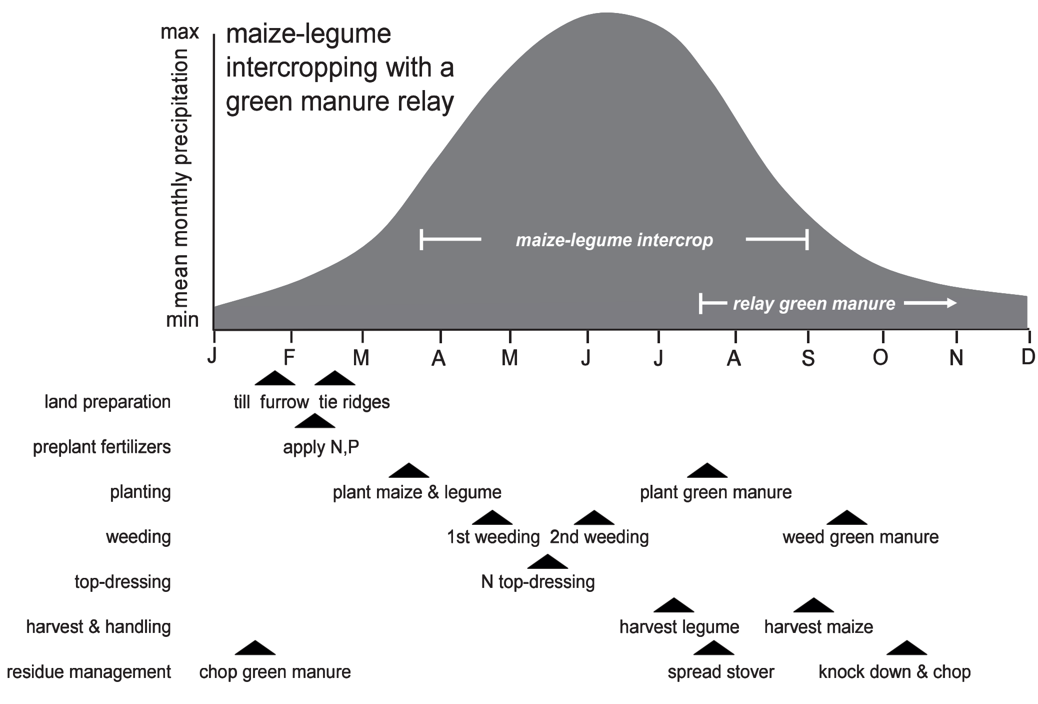


Figure 6.2. An ISFM management scenario suitable for cereal and grain legume production within a semi-humid, monomodal rainfall regime

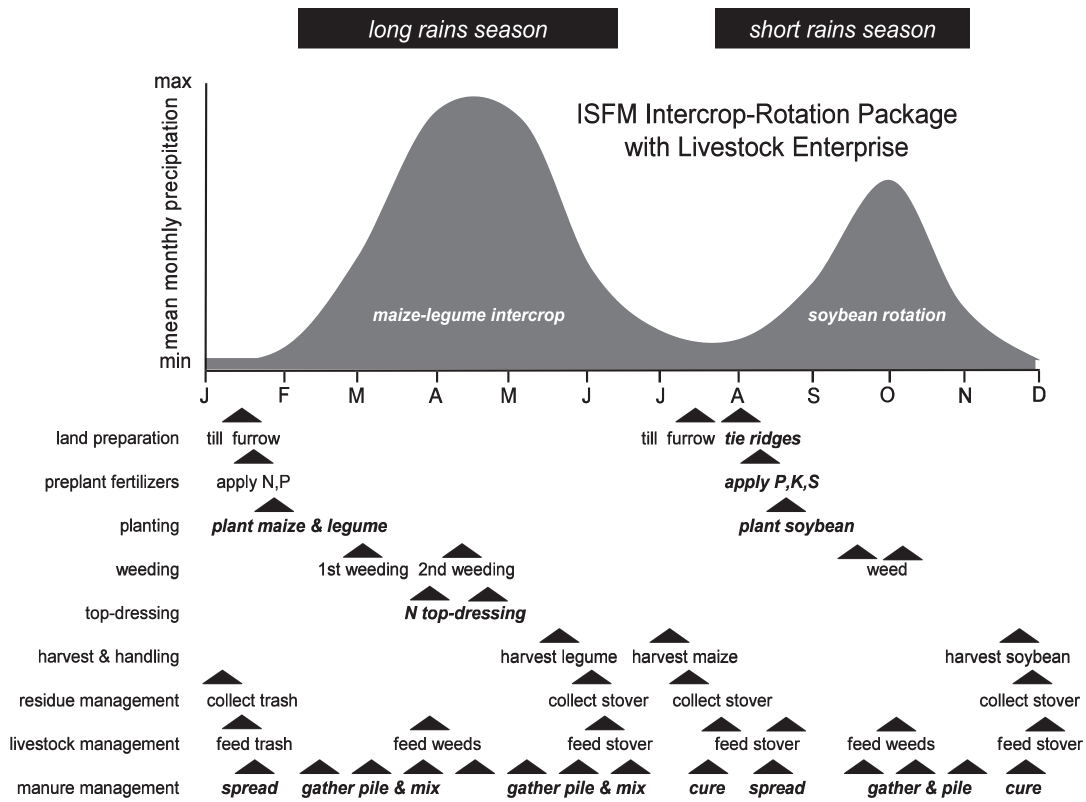


Figure 6.3. An ISFM package designed for cereal-legume cropping and livestock enterprise in a sub-humid climate with a pronounced bimodal precipitation pattern.

wastes. Mineral materials such as rock phosphate or coarse limestone may also be applied at this time to accelerate their solubilization. After heating and cooling, these piles are cured (dried) and then spread across the field after tillage but before furrowing or bed preparation. Two tons of composted manure can substitute for 100 kg of pre-plant fertilizer, and greatly improve the nutrient use efficiency of additional fertilizers. This scenario is intended to illustrate that ISFM is a flexible year-round pursuit that enhances the beneficial interactions between different farm enterprises.

Refinements to ISFM Practice

Adjustments by poorest households. Farm households with the poorest resource endowments typically have smaller farms, few or no livestock, less available labor and a larger proportion of the farm committed to subsistence food production. Another characteristic of the poorest households is that they are usually bypassed by important technological and economic developments, and ISFM will have little impact if it requires investment levels that act in the same way. For these reasons, it is critical that ISFM be flexibly applied by households with the lowest resource endowments. The poorest households must purchase mineral fertilizers more sparingly and apply them more strategically. Less expensive forms of mineral nitrogen and phosphorus, such as urea and rock phosphate, respectively, and purchasing mineral fertilizers in smaller amounts increase nutrient acquisition. Applying nitrogen fertilizer as micro-dosed top-dressing to vegetative crops increases its use efficiency. In some cases, farmers may top-dress individual plants using bottle caps that deliver between 2 and 3 grams per dose. In general, the poorest households fertilize individual plants, while more affluent ones improve entire fields.

Poorer households find additional advantage in reliance upon grain legumes and BNF. Too often uninformed farmers have incomplete understanding of root nodulation and symbiosis, but they readily recognize when legumes are green and healthy while companion crops lack vigor. Composting organic resources is often a more available option to poorer households because they have fewer ruminant livestock to feed. At the same time, the absence of manure as a compost ingredient requires that compost inputs be more carefully blended. Indeed, the best means of escaping poverty is through increased market engagement, whether by intensive gardening, collective grain marketing or cottage industry. Livestock enterprise is often the most immediate opportunity that not only generates income and improves household diets but also provides a source of manure for use in soil fertility management.

Adjustments on slopes. The threat of soil erosion increases with slope and results in irreversible loss of soil health. Soil conservation thus occupies a central role in hillside agriculture and soil fertility management practice must complement these precautions. Erosion control is largely achieved through the constructions of bench terraces, bunds, ditches and rock lines and through the establishment of contour furrows, grass strips and hedgerows. Erosion may also result from the exposed pathways formed by humans and livestock, providing incentive to stabilize pathways and confine large livestock.

Several routine field practices that check erosion also assist in nutrient and organic matter recycling. Forming trash lines from cereal stalks and legume trash along the slope contour following grain harvest impede runoff and sheet erosion. So too does spreading these materials as mulch. Hedgerows planted along field and farm boundaries stabilize slopes with their roots and may be trimmed as a source of organic inputs. Cover cropping and relay green manures that extend into or through the dry season also protect of the soil surface.

Adjustments in sands. Sandy soils pose a unique set of production constraints and opportunities. These soils have low water holding and nutrient retention capacities but readily accommodate organic inputs. Nutrients in sandy soils are predisposed to leaching but at the same time nutrients within the root zone are not immobilized by clays. Organic matter is more completely mineralized because the mineral fraction is too coarse to physically complex with humus but nutrients within those organic inputs are more quickly mineralized. Sandy slopes are more subject to water erosion because the soils lack strong aggregation but they are well drained and readily worked using hand tools. They are often light in color and resist over-heating. The term sand describes particle size and not mineralogy that may vary between silicate, carbonate or volcanic materials. Silicates have a low but weakly buffered pH. Carbonates possess a high pH that can interfere with micronutrient availability. Volcanic sands may be rich in base nutrients and sulfur. In some cases, sands are extremely low in soil organic matter and nutrient and moisture holding capacities, resulting in inadequate response to mineral fertilizers.

Several adjustments to soil fertility management are available for sandy soils. Withholding mineral nitrogen from pre-plant fertilization and then applying it in split applications timed to rains reduces nitrogen leaching (Piha 1993). Applying surface mulch protects the soil from drying and provides a continuous source of comminuting organic inputs. Soil organic matter building is more difficult in sandy soils but the benefits from its increases are more pronounced (Woomer *et al*. 1994). Deep sands are not a suitable habitat for termites permitting greater targeting of organic inputs. In shallow sands with underlying clays, emergent termite mound provide niches of soil with improved physical and chemical characteristics (Okello-Oloya and Spain 1986). Sands are particularly well suited to Conservation Agriculture because seed planting by drilling requires less energy and minimum tillage promotes soil organic matter building (see Chapter 10).

Agroforestry options. Agroforestry involves the management of trees within cultivated land and in many ways represents its own complex sub-discipline. Agroforestry interacts with ISFM in many ways through the recovery, processing and application of tree prunings as organic inputs to soil. Many agroforestry tree species are N-fixing and their prunings and litterfall recycle nutrients to the soil (Young 1989). Trees are deep-rooted compared to annual crops and can recover nutrients from lower soil horizons (Mekonnen *et al.* 1997). Trees have both above- and below-ground competitive advantage over field crops owing to their stature and root distribution and the challenge before land managers is to derive advantage from trees without compromising their main production enterprises (Ong and Black 1995). An obvious niche for trees is along field and farm boundaries assuming that the individual fields (or farms) are not too small. A particularly effective means of harnessing advantage from trees is obtained when prunings provide cut fodder to livestock and their manure is applied to field crops (Young 1989). Another is the establishment of multi-purpose trees as orchard-woodlots provided that smallholders have the space and time to devote toward this operation. Care must be exercised, however, in too closely integrating field crop and tree production as excessive labor may be required to keep perennial competitive advantage in check. Proven exceptions to this rule exist, however, such as the establishment of cereal and legumes beneath and around *Faidherbia albida* in semi-arid climates (Vandenbeldt 1992) or the establishment of scattered fruit trees in fields. This generalization is also not applicable to multistory tree gardens characteristic to the humid tropics (Young 1989).

Farming on forest margins. Farmers living within or along the margins of forests have developed traditions of slash-and-burn agriculture where forests are cut, burned and cultivated until they are no longer productive (see Chapter 9). Abandoned land then recovers over time and new or recovered areas are subjected to another round of slash-and-burn (Nye and Greenland 1960). These farmers neither apply external inputs nor do they practice basic soil conservation. In a scarcely populated setting with abundant forest resources, slash-and-burn represents an expedient means of household subsistence. In today's world of dwindling tropical forests and global climate change, slash-and-burn represents a threat to human survival and the wasteful destruction of forest and biological resources (Brady 1996). Adoption of several ISFM principles by these farmers will permit prolonged, if not permanent, cultivation along tropical forest margins (see Chapter 9).

Plant nutrients and soils are better conserved during land conversion from forest to cropland through relatively simple field practices. Felling trees along rather than against the slope contour establishes small bench terraces that resist erosion. Reduced burning prevents the volatilization and loss of nitrogen and extends the mineralization of phosphorus and nutrient bases. Typically, slash-and-burn practitioners do not rely upon mineral fertilizers, soil amendments or even locally gathered organic resources, rather they move to new forest margins or older fallows once soils become exhausted. The application of small amounts of fertilizer, the adjustment of acidic soils with lime and the collection and use of abundant nearby organic resources stand to greatly extend the productive capacity of soils along forest margins (Palm *et al.* 1996). Heavy mulching can also suppress weeds and impede plant succession. Indeed, one of the strongest applications of agroforestry is the establishment of multi-layer perennial gardens that provide combinations of food and market crops along forest margins (LiYu *et al.* 1996). One means to support this end is to establish tree tenure among land managers who would otherwise deplete soil health and then fell new forests.

Organic farming systems. The philosophy of organic farming maintains that the use of manufactured farm inputs is detrimental to humans and the environment. These farmers rely entirely upon nutrient recycling, organic inputs and raw agro-minerals as sources of nutrient inputs and denounce the use of processed mineral fertilizers and most agro-chemicals (Lampkin 1990). Without being judgmental towards its tenants, organic farming practices embody many of the same principles of ISFM with regards to the recovery, processing and use of organic resources, and advances very sophisticated forms of composting.

Nutrient recycling within organic farms is mainly achieved through the application of manures and composts although restrictions limit which organic inputs may be processed (Harris

Field practice	Importance to land management adjustments					
	poorest households	cultivated slopes	cultivated sands	agro-forestry	forest margins	organic farming
Replace nutrient losses regularly	+	++	++	±	++	-
Micro-dose individual plants	++	±	+	-	+	-
Apply nitrogen top-dressing	+	+	++	±	+	-
Replenish long-term nutrient loss	++	+	+	±	-	-
Practice patch amelioration	+	+	+	+	-	±
Combine mineral and organic inputs	++	+	++	±	±	-
legume intercropping or rotation	++	+	++	±	+	++
Inoculate legume seed with rhizobia	±	±	±	±	±	±
cover crops and green manures	±	++	++	+	-	+
Establish N-fixing trees on boundaries	+	+	+	++	-	+
Establish trash lines along contour	±	+	-	-	±	+
Recover biomass from boundary areas	+	±	+	++	++	+
Revegetate degraded and eroded areas	+	++	±	++	-	±
Increase herd size and quality	++	±	+	+	-	+
Improve diet and manure quality	+	+	+	++	-	+
Increase efficiency of manure recovery	++	±	+	±	-	++
Improve handling & compost processing	++	±	+	+	++	++
Stubble and tether grazing	+	-	+	-	-	±

- signifies not applicable, ± is of minor importance, + indicates complementarily and ++ identifies a key adjustment

et al. 2002). For example, manure from livestock that have not been raised organically because they have received antibiotics or growth stimulants cannot be applied directly, rather it must be composted for several months. The same is true for crop residues that were treated with pesticides during their production. Organic farmers also rely upon BNF and agro-minerals as a means of acquiring nutrients and practice improved fallows, green manures and crop rotation for a variety of purposes. The organic mandate may require that farmers produce compost teas and slurries that readily correct nutrient imbalance in established plants, practices that other farmers may consider too labor requiring and indirect. Organic farmers most often direct their soil fertility management through pre-plant application of nutrient-rich organic inputs and subsequent mulching. Organic practices are mandated and producers are certified through various bodies (Rundgren 1998; Kanyarati and Moselund 2003) and become eligible for the higher prices that organic produce commands (Browne *et al.* 2000).

The land management practices presented in Table 6.5 have different importance to farmers' adjustments in ISFM depending upon agro-ecological setting and production strategies. More strategic use of mineral fertilizers, their combination of mineral and organic resources, intensification of legume and animal enterprises and composting offer special advantage to resource-poor households. Cover cropping and revegetation are important on slopes in order to control erosion. Sands benefit from greater amounts and better used organic inputs. Agroforestry improves access to organic inputs, livestock feed, and also serves to stabilize slopes. Farming on forest margins provides access to organic inputs and land managers must emphasize those practices that permit longer-term cultivation, but often lack access to livestock manures and purchased farm inputs. The tenants of organic farming prohibit practices involving mineral fertilizers, but have access to a wide array of organic resource management options. Conservation Agriculture relies heavily upon green manuring and surface mulching, and is discussed in further detail in Chapter 10. This chapter has described the products applied in ISFM, and the practices that permit greater integration of farm resources in a generalized manner. More specific strategies are often dependent upon the restrictions and opportunities posed by climate and soils. The following three chapters describe ISFM practices specific to farming systems in African drylands (Chapter 7), moist savannas and woodlands (Chapter 8) and the humid forest zone (Chapter 9).

Chapter 7. ISFM practice in drylands

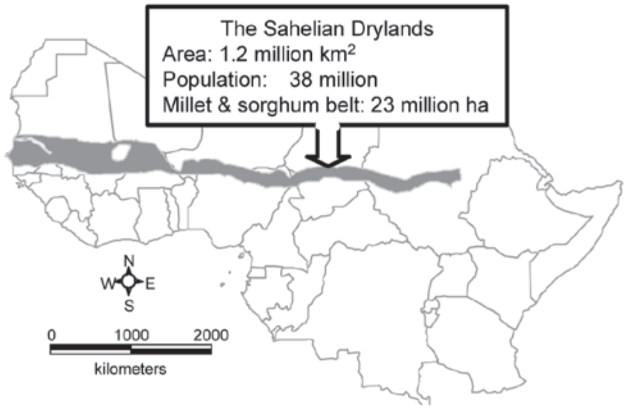


Figure 7.1. The Sahelian Drylands is an agricultural belt vulnerable to drought that stretches between Senegal and Sudan.

Dryland farming in Africa is a necessity in the 1.2 million square kilometers of the Sahel, an area that supports a population of 38 million persons through the cultivation of 23 million hectares (Figure 7.1). This zone is contained within the Sahel Regional Transition Zone (White 1983), a 400 km wide band stretching from the Atlantic Ocean into the Sudan. The Sahel is a relatively flat to gently undulating landscape below 600 meters in elevation with unreliable, monomodal rainfall between 150 to 500 mm per year. This rainfall occurs between June and September and may be deposited by only a few heavy storms. Mean annual temperatures range between 25° and 29° and highs can exceed 40° during the summer. The natural vegetation ranges from semi-desert in the north to woody grassland in the south with large areas of bushland. The zone contains about 1200 plant species but few endemics. Immediately to the south is the Sudanian Zone that is level and undulating, wetter (500 to 1000 mm yr^{-1}) and characterized by woody savanna that has largely been converted to agriculture (White 1983). Millet is widely grown in the Sahel and Sudanese zones, but so too is sorghum and maize. Semi-nomadic pastoralism is widely practiced and overgrazing has led to extensive land degradation and desertification. Farming is perilous in the Sahel owing to severe and cyclical droughts. From West to East, this zone includes northern Senegal, southern Mauritania, Mali, northern Burkina Faso, northern Nigeria, Niger, the northern tip of Cameroon, Chad and Sudan. Dryland farming also occurs in parts of Southern Africa near the fringes of the Namibia and Kalahari Deserts but this area is not considered in detail within this chapter. Nonetheless, many of the ISFM principles and practices described for the Sahel in this chapter are relevant to Southern Africa and elsewhere.

The soils of the Sahelian drylands are dominated by Arenosols and Cambisols with small areas of Vertisols (FAO 1977). Arenosols are mainly composed of quartz sand but express some horizontal development. These sandy soils have very low moisture holding and nutrient retention capacities. Cambisols are not unique to drylands and represent a recent stage of soil development. The Calcic Cambisols occurring in the Sahel tend to be more fertile than Arenosols but are also severely constrained by the availability of moisture. Vertisols are heavy, dark clays dominated by montmorillionite that exhibit deep surface cracks during the dry season. At the onset of the rains these cracks fill with surface debris carried by runoff and then close due to soil swelling (shrink-swell) and in this way the soils invert over time, forming deep, dark surface horizons. These soils are quite fertile but management of their physical properties pose a challenge to farmers as field operations prove difficult during both the Vertisol's wet and dry state. Other soil types in the Sahel include Lithisols, Regosols and Luvisols, all of which tend to occur in more hilly terrain and are low in soil organic matter and nutrients.

Soil limitations in the Sahel reflect these soil types. Soils exhibit low water holding and cation exchange capacities and are often acidic (Table 7.1). Bationo (2008) described agricultural soils supporting millet-based production in the Sahel in terms of their physical and chemical characteristics (Table 7.2). These soils are quite sandy, with low organic matter, water holding and nutrient retention (Bationio and Mokwunye 1987). While base saturation is relatively high, the amount of nutrient bases is quite low owing to low CEC. Note that nitrogen, extractable phosphorus and exchangeable potassium are also present in low amounts. Because of their unfavorable soil physical properties and low nutrient reserves, agricultural soils of the Sahelian drylands present a challenge to farmers in terms of practicing ISFM (FAO 2002b).

Table 7.1. Limitations in selected Sahelian soils based upon data from Burkina Faso, Mali, Niger and Senegal (after Bationo 2008)

Soil limitation	proportion (%)
low water holding capacity	32
acidic	22
low CEC	19
shallow	18
erosion prone	12
poorly drained	10
shrink-swell	4

The Legacy of Drought

Drought is the leading biophysical cause of food insecurity and human suffering in the Sahel. Three quarters of the world's severe droughts over the past 15 years have occurred in Africa. Over 34% of Africa's population live in arid and semi-arid environments (about 230 million persons). Over the past three decades, severe drought has occurred in Eastern, West or Southern Africa in 1967-1974, 1973-74, 1981-1987, 1991-1994 and 1999-2003. Prolonged drought in West Africa's Sahel during 1972-1984 killed over 100,000 persons and placed 750,000 more totally dependent upon food aid. In Ethiopia during 1984, 8.7 million poor farmers were affected, killing over 1 million persons and 1.5 million livestock.

Severe drought accounts for half the world's food emergencies annually (FAO 2004a). In 2003, the World Food Program spent US $565 million in response to drought in SSA and approximately 20 million metric tons of potential tropical maize production is lost each year due to drought (Doering 2005). There are also broader, more systemic effects of drought beyond food insecurity such as decreased household income, the loss of assets due to slaughter of livestock, health threats due to the lack of clean water for hygiene and household uses, environmental degradation, and less sustainable land management. While food aid undoubtedly saves lives, it is an expensive and short-term approach to combat the consequences of drought that must be complemented by projects that effectively address the fundamental problem of agricultural productivity in African drylands.

While much world attention is focused upon Africa's more recent drought induced famines, the continent is experiencing a much longer drying trend. Based upon changing lakebed levels in the 19th Century and rainfall records during the 20th Century, Nicholson (2001) concluded that Africa experienced a drying trend for the last two centuries. Rainfall was reduced by 20-40% in the Sahel over the past 30 years but a similar dry episode occurred in the early 19th century. Only a few centuries ago, woodlands grew to the margins of what is desert today and desert countries such as Mali and Sudan were covered with grasslands (Nicholson 2001). Meanwhile, temperatures in Africa remain unchanged. Avery (2002) strongly asserts that global warming and African droughts are not related and those who differ are doing so for political or institutional purposes. Herlocker (1999) argues that agricultural droughts too often result from

Table 7.2. Characteristics of Sahelian agricultural soils where millet is produced (after Bationo 2008)

variable	mean	range
sand (%)	88	70-90
clay(%)	3	0.7-0.9
pH (H_2O)	6.1	5.2-68
organic matter (%)	0.9	0.14-1.9
total N (mg kg-1)	184	31-336
extractable P (mg kg-1)	5	1-112
total P (mg kg-1)	95	25-191
CEC (cmol kg-1)	1.8	0.54-3.6
exchangeable K (cmol kg-1)	0.1	0.03-0.33
exchangeable Ca (cmol kg-1)	1.2	0.15-264
exchangeable Mg (cmol kg-1)	0.4	0.02-0.94

overgrazing and the cultivation of crops poorly suited to available moisture and that drought is more likely to occur on degraded lands. Nicholson (2001) simply concludes that natural climate variation still outweighs anthropogenic effects but complex feedback mechanisms exist. Clearly, farmers in the Sahel are acutely aware of drought as a chronic risk and must adjust their cropping strategies accordingly, seeking to take the best advantage of limited moisture availability, in part through improved soil fertility management.

Farming system characteristics

Farmers in the Sahel are typically communal, living in central villages and farming land assigned to their families through village leaders (Vedeld 2000). Population densities in the agricultural areas remain relatively low, with 0.5 to 1.5 ha available per capita (Bationo 2008). Land availability alone does not assure rural prosperity in the Sahel owing to the poor crop productivity resulting from low rainfall and chronic risk of drought. The cropping systems are typically based upon millet, sorghum, groundnut and cowpea, with millet-groundnut rotations most common. Planting densities are low and intercropping is sometimes discouraged because of unreliable moisture availability. Livestock operations are closely integrated with cropping with cattle feeding upon the crop residues and providing sources of traction and manure. Indeed, given the severe soil limitations in agricultural lands, manure management offers farmers a seasonal opportunity to improve soils through manure collection, storage and application (Powell *et al.* 1996). Fertilizer consumption remains among the lowest in the world, with only 1.1 kg ha^{-1} yr^{-1} applied in Niger and up to 9.0 kg applied in neighbouring Mali. Crop areas and average yields for selected Sahelian countries are presented in Table 7.3. Millet is the most widespread cereal but offers lower yields. The better performance of maize is due in part to its production within higher potential lands. Cassava is also produced, covers 40,000 ha and produces an average 10.7 tons of fresh tubers ha^{-1} (data not presented).

Best management practices

The principles of ISFM in dryland farming involve 1) maximizing water capture and eliminating runoff, 2) protecting soils from water and wind erosion, 3) managing limited available organic resources to compensate for unfavorable soil physical properties and 4) strategic application of mineral fertilizers. To a large extent, the technologies required to practice dryland ISFM are available through the development of planting pits and tie ridges, establishment of bunds and stone lines, boundary tree planting, beneficial crop and livestock interactions and strategic timing and placement of mineral fertilizers at judiciously applied rates. Despite these technical advances, dryland agriculture remains risky because of unreliable availability of moisture, a condition that is best corrected whenever possible by further development of irrigation.

Table 7.3. Cereal coverage and yields in five selected Sahelian countries (based on FAO 2004a)

country	maize		millet		sorghum	
	area x 1000 ha	yield kg ha^{-1}	area x 1000 ha	yield kg ha^{-1}	area x 1000 ha	yield kg ha^{-1}
Burkina Faso	317	1768	1284	705	1396	894
Chad	134	664	783	434	712	640
Mali	246	1212	1260	636	767	756
Niger	8	711	5194	423	2487	228
Sudan	75	742	2370	233	4980	641
Total (average)	781	(911)	10890	(367)	10342	(528)

Table 7.4. Effect of *zai* pits and ISFM measures on sorghum yields in West Africa. Adopted from Reij *et al.* (1996).

water & fertilizer management	sorghum grain (kg ha^{-1})
zai planting pits	200
zai + Cattle manure (CM)	700
zai + Mineral fertilizers (F)	1400
zai + CM + F	1700

Water harvesting. Water harvesting and moisture conservation are essential to successful farming in the Sahel and is best combined with ISFM to improve crop performance in this harsh and changing climate (Table 7.4). Micro-catchment approaches to water harvesting in the Sahel include planting pits locally known as *zai*, half moon bunds, tied ridges and rock lines. *Zai* pits are an ancestral approach to dryland farming developed in Burkina Faso where shallow basins of 20-30 cm diameter (sometimes up to 80 cm) and 10-15 cm deep are established (Olufunke *et al.* 2004). Rainfall is captured within the pit and directed toward its center. This technique is also used to rehabilitate crusted and degraded lands. Half moons are small, crescent-shaped earthen bunds that direct runoff toward a centrally-placed planting hole. Tied ridges that close furrows are also an option for improved rainfall capture. All of these techniques are intended to improve soil moisture status (Cofie *et al.* 2004; Kandji *et al.* 2006). Water harvesting technologies that increase infiltration by 50% can improve grain production by 60 to 90% depending upon precipitation and soil fertility (Day and Aillery 1988).

Reij and Thiombiano (2003) documented how the Central Plateau of Burkina Faso, after periods of major land degradation and out-migration, underwent significant change. Millet and sorghum yields improved from approximately 400 kg ha^{-1} in 1984-1988 to 650 kg ha^{-1} in 1996-2000. The increase was mainly due to major investments in soil and water conservation in combination with other components of ISFM. Increased investment in livestock, accompanied by improved management led to increased availability of manure. Improved livestock management also led to regeneration of local vegetation and greater availability of forage. Other examples of improved dryland management include the adoption of compost pits fortified with ground rock phosphate and the installation of stone rows and *Andropogon* grass strips. Over 200,000 such compost pits were documented in Burkina Faso in 2002. Stone rows and grass strips are critical erosion and runoff control features that combined with fertilizer and manure improved crop yields by 65% and 142%, respectively. In the process, water use efficiency increased by 100% (Zougmoré *et al.* 2003).

The success of *zai* planting pits has been documented throughout the Sahel. In 1989-1990, a project implemented by the Djenné Agricultural Systems showed that agricultural yields increased by over 1000 kg ha^{-1} compared to traditionally ploughed control plots. In Niger, Hassane *et al.* (2000) and Hassane (1996) observed average cereal yields of 125 kg ha^{-1} on untreated fields and 513 kg ha^{-1} in pitted fields with a minimum of 297 kg ha^{-1} for 1992 and a maximum of 969 kg ha^{-1} for 1994. Reij and Thiombiano (2003) have also reported higher sorghum grain yields when the planting pits were amended with organic and inorganic nutrient sources, indicating the importance of nutrient management in further improving the performance of the *zai* technology. Other studies have also demonstrated improved water and nutrient use efficiencies from the combination of water harvesting and nutrient application thus giving a win-win situation.

Variability of rainfall is a critical factor affecting efficiency of fertilizer use and in determining risk-aversion strategies of farmers in the Sahel (Morris *et al.* 2007). A survey of available data found African levels of available water from rainfall were only 127 mm yr^{-1} compared to North America with 258, South America with 648 and the world average of 249 mm yr^{-1} (Brady 1990). Water productivity can be doubled if appropriate soil, water and nutrient management practices are put in place. Water harvesting without soil fertility improvement will not increase crop production, especially in the drylands (Table 7.4). Fertilizer is commonly thought to increase risk in dryland farming, but in most situations, its use is even risk-reducing. Phosphorus in shorter-duration millet varieties in Niger, for example, cause crops to grow hardier and mature earlier, reducing damage from and exposure to drought (ICRISAT 1985-88; Shapiro and Sanders 1998). Table 7.4 indicates how the improvement of soil fertility can increase water use efficiency in a stepwise manner.

Soil conservation. Soil conservation is critical to improved nutrient management and crop productivity in the Sahel to counter the threat of water erosion from peak rainfall and wind erosion during the extended dry season. Conservation measures along the slope contour also capture water through short-term storage and greater infiltration into the soil. Means to conserve soil include the establishment of stone lines, the construction of bunds and the planting, maintenance and utilization of grass, shrubs and trees along field and farm boundaries.

Constructing rock bunds along the contour is one of the most effective means of reducing soil erosion and increasing water infiltration in the Sahel. Stone bunds are positioned at distances between 10 and 50 meters apart depending upon the slope and the availability of stones. In rocky lands, individual farmers can build their own bunds 20 meters apart but where rocks are scarce, this operation is best performed through farmer collective action at much wider spacing (Zougmoré 2000). These two approaches require between 100 and 425 hours of farm labor per ha, respectively, with costs increasing eight-fold if rocks must be transported by truck. One advantage of stone lines over earthen soil bunds is that some runoff is able to pass through the lines reducing waterlogging of the soil upslope from the bunds. Cereal yields may increase by 50% to 100% following construction of bunds (Wright 1985, Vlaar 1992) but the structures require annual maintenance to perform optimally (Zougmoré 2000). This technique is also proven effective in recovering marginal lands to agriculture (FAO 2001a,b). Short earthen bunds covered with grass strips serve a similar function although they may be eroded by heavy rains and grass is slow to recover after a long hot dry season (Zougmoré *et al.* 2003). These conservation measures may be interspersed with trees to form shelterbelts that protect from wind erosion. The design of these windbreaks combines several shrub and tree species of different shapes to maximize their effects. Additional benefits of shelterbelts include microclimate amelioration and improved soil fertility as leaf litter is blown or spread into adjacent fields (Young 1989).

Organic resource management. The management of organic resources within cereal-based cropping in the Sahel is conditioned by two major factors, the huge competing demand for crop residues as livestock feed, fuel and structural material, and the importance of livestock as a source of manure. The consequence of poor organic resource management is the decline of soil organic matter and the resulting decline in soil nutrient retention, water holding capacity and mineral fertilizer use efficiency (Manu *et al.* 1991). For example, a decline of 1.0 g of soil carbon per kg of soil results in the reduction of CEC by 0.25 cmol (De Ridder and Van Keulen 1991), an effect that extrapolated may result in the reduced retention of between 80 and 150 kg of base nutrients per ha in a sandy soil (assuming a bulk density of 1.5 kg l^{-1} and base saturation of 50%). Owing to their sandy nature, many Sahelian soils are more dependent upon soil organic matter than clay for their nutrient and water buffering capacities (Bationo 2008).

Many Sahelian farmers continue to practice burning as a component of land preparation, a practice that effectively mobilizes nutrient bases but may result in the loss of 40 kg N and 10 kg S per hectare each cropping cycle. Burning reduces soil microbial activity and contributes to the massive nutrient loss from Sahelian soils (Bationo 2008). Conversion of a sandy Senegalese soil from secondary woody vegetation to agriculture resulted in the loss of about 1.1 ton ha^{-1} yr^{-1} of soil organic carbon over 12 years (Woomer *et al.* 1994) but this trend is reversible, as improved organic resource management (eliminate burning, mulched straw) accumulated about 0.51 tons C ha^{-1} yr^{-1} over three years (Feller *et al.* 1987). Cereal crop residues are an extremely important household organic resource in the Sahelian and Sudanese zones with two of these applications, livestock feed and soil input, having important complementary applications within ISFM. The characteristics of these resources may interact, as when crop residues are mixed with urea to improve their nutritional value and digestibility by ruminant livestock, which in turn improves the quality of manure they produce.

Strategic mineral fertilization. Applying small amounts of mineral fertilizer to individual planting stations within fields where water conservation is practiced is an important means to improve crop yields in African drylands. This approach is referred to as micro-dosing and is being adopted in many areas of the Sahel, particularly Burkina Faso, Mali and Niger. Farmers in the Sahel first adopted micro-dosing as a fertilizer application strategy in a modest way where it is popularly known as the Coca-Cola technique because a soda bottle cap is used to allocate fertilizer (Tabo *et al.* 2006). Micro-dosing refers to the utilization of relatively low quantities of fertilizer through point placement in cereal-based systems. The rate of fertilizer application is about one-third of the recommended rates for the area. Small amounts of fertilizers are more affordable to farmers, give an economically optimum (though not biologically maximum) response, and if placed in the root zone of these widely-spaced crops rather than uniformly distributed, result in more efficient uptake (Bationo and Buerkert 2001). Yields of millet and sorghum have been observed to be between 43 and 120% higher when using fertilizer micro-dosing than with the earlier recommended fertilizer broadcasting rates and farmers' practices respectively (Tabo *et al.* 2006). Micro-dosing is best practiced in conjunction with other technologies such as water harvesting, or application of manure, crop residues, or household waste. Crops under micro-dosing have been observed to perform better under drought conditions because the crops larger root systems are more efficient at finding water, and fertilizer hastens crop maturity, avoiding late-season drought.

Similar fertilizer extension strategies are practiced in the drylands of East and Southern Africa as well. Small packages of seeds and complete fertilizer blends are disseminated by Farm Inputs Promotions in semi-arid Eastern Kenya. Marketing seeds and fertilizers in small quantities at local markets to first-time and women buyers effectively created demand for additional farm inputs from agro-dealers (Blackie and Albright 2005). In post-drought recovery programs in Zimbabwe in 2003 and 2004, 170,000 farmers were provided 25 kg bags of ammonium nitrate with advice on how to apply this to one acre. Most farmers obtained a 30-50 percent yield increase, and more than 40,000 tons of additional grain were produced. This extra production reduced the costs of Zimbabwe's food aid imports by more than US $8 million. In Malawi, micro-dosing was initiated through the Starter Pack program. Distribution of Starter Packs was intended as a subsidized support package to overcome famine and declining soil fertility (Blackie and Mann 2005; Snapp *et al.* 2003.). It was successful in achieving short-term food security and, in retrospect, discontinuation of the program was a major contributor to Malawi's food crisis in 2002. More recently, Malawi has established active support and smart subsidies for its farm input supply sector that has resulted in food surpluses and maize exports for the first time in decades (Denning *et al.* 2009).

Phosphorus is frequently the nutrient most limiting crop production within Sudano-Sahelian agriculture (Bationo 2008). This deficiency results from four factors; 1) the soil parent material and resulting sands are low in phosphorus, 2) soil organic matter and organic phosphorus are declining and its recycling is slow, 3) the presence of oxides result in phosphorus occlusion and 4) prolonged cropping without fertilizer application has further reduced already low soil phosphorus reserves (Manu *et al.* 1991). While application levels as low as 4 kg P per ha have resulted in crop response (Jones and Wild 1975), recommended levels of P addition to deficient soils range between 15 and 30 kg P ha^{-1}. Soil test values of 2 or 3 mg extractable P kg^{-1} of soil are not uncommon and increasing P to 5 mg kg^{-1} can increase cereal yields by 50 to 180% (Bationo 2008). In many cases, further large gains in yield are achieved by applying mineral nitrogen and potassium or by combining phosphorus application with manure.

West Africa is rich in sedimentary sources of phosphorus with no less than 16 major deposits in West Africa's drylands (van Kauwenbergh 2006). The effectiveness of phosphate rock as a direct amendment to soils varies with a deposit's chemical composition, its particle size and reactive soil properties but it is ultimately controlled by the rate of isomorphic substitution of carbonate for phosphate within apatite crystalline structure (Mokwunye 1995). In some cases, rock may fail to react and release phosphorus during the first season, but in others its phosphorus use efficiency can exceed that of triple super phosphate (Bado *et al.* 1998). Phosphorus release by poorer quality rock is readily improved through partial acidulation, increasing P availability by about 10% relative to mineral fertilizers, but this benefit does not greatly compromise the P release over several years. Some reports for quite small amounts of superphosphate fertilizer and Kodjari and Tahoua phosphate rock applied to cereals and field legumes in the Sahel are truly spectacular (see Bationo 2008). Again, yield response to phosphate strongly interacts with nitrogen availability and organic resource management (Figure 7.2).

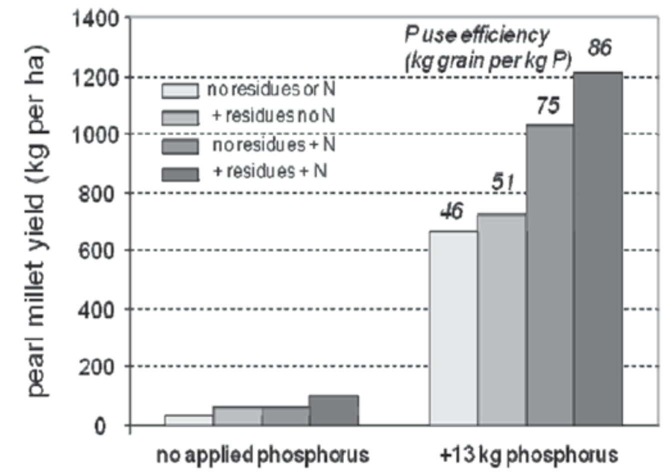


Figure 7.2. Effect of fertilizer and crop residue on pearl millet yield in Sadore, Niger (after Bationo 2008).

Integrating land management practice

Micro-dosed application of mineral fertilizers is best practiced in conjunction with other key technologies such as the *zai* planting holes (Figure 7.2), addition of livestock manure or crop residue and compost prepared from household and garden wastes. The use of planting pits, stone bunds and ridges in the drylands have been observed to conserve water and increase crop production. The *zai* pits are often filled with organic matter so that moisture can be trapped and stored more easily. The pits are then planted with annual crops such as millet or sorghum. The *zai* pits extend the favorable conditions for soil infiltration after runoff, and the pits are also beneficial during storms, when there is too much water. The compost and organic matter in the pits absorb excess water, resulting in additional water storage. Applying mineral fertilizer and manure to these pits in Central Burkina Faso increased sorghum yields from 200 to 1,700 kg ha^{-1}, a remarkable 7.5-fold improvement. Adopters receive benefits to this ISFM practice during both favorable and poorer growing seasons (Reij and Thiombiano 2003).

Improving cultural practices associated with soil fertility input use can significantly increase fertilizer use efficiency and subsequent crop productivity. Dryland farmers in Kenya can double their yields by placing fertilizer 5 cm below and to the side of maize seed at planting rather than applying it directly above (Poulton *et al.* 2006). By concentrating fertilizer applications in shallow basins similar to *zai* practiced in conjunction with liming and better weeding, farmers in Zambia raised maize yields from one ton per hectare to six or more. Similarly in West Africa, much higher fertilizer use efficiency resulted from sound agronomic practices (Bationo *et al.* 1997). For example, under low management intensity, farmers obtained only 885 kg ha^{-1} compared to 2775 kg ha^{-1} of maize through use of a recommended soil fertility management package (Figure 7.3).

Several application techniques facilitate better use of the limited quantities of fertilizer (Bationo and Mokwunye 1987). Figure 7.4 illustrates how the AE of fertilizer use is increased 2.8 fold in sorghum through the construction of *zai* planting pits. Broadcast SSP fertilizer application at a rate of 13 kg ha^{-1} can be reduced to 4 kg P ha^{-1} by hill placement without yield loss and the agronomic efficiency is increased from 26 to 98 kg grains per kg of P applied. Efficient N utilization in maize production systems can be realized by appropriate placement and timing of N fertilizer. A small amount is supplied before planting for early crop growth, while the major dose is applied when the maize has reached knee-height and needs its N most. An effective practice for maize in Zimbabwe is to withhold N application at planting to avoid losses during the early heavy rains and to instead is applied in about 3 split applications based upon seasonal rainfall pattern. This approach works best in dry or average years, but also in seasons when rains are well above average.

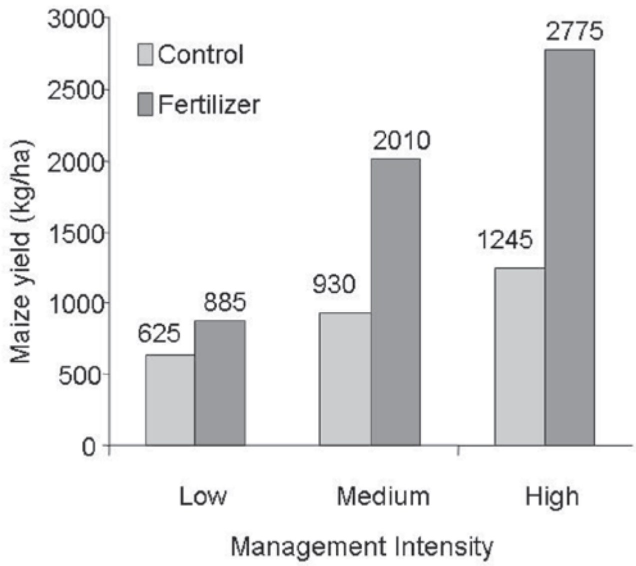


Figure 7.3. The effect of management intensity (planting date, crop density and time of phosphorus application) on maize grain yield at Tinfouga, Mali (Bationo *et al.* 1997).

Investing in dryland farming

Several factors have been identified as major constraints to the widespread adoption of micro-dose technology. These include weak access to fertilizer credit, insufficient flows of information and training to farmers and inadequate policies. Successful experience from Niger has shown that adoption of micro-dose technology requires supportive and complementary institutional innovation and market linkage. Various strategies have been initiated that facilitate ISFM including the formation of farmer's marketing co-operatives referred to in French as *warrantage*. This system developed from the observation that the price of produce, in this case millet, increases up to 3-fold during the 10 months after the harvest, suggesting that farmers can benefit from better prices if they delay sales of their produce for several months. As the micro-dose method increases yields by at least 50%, farmers may put off the sale of a

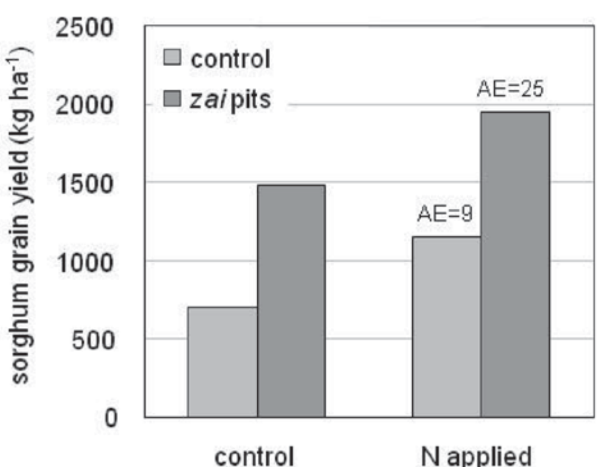


Figure 7.4. Sorghum yields obtained using *Zai* pits and urea application at 50 kg N ha^{-1} at Tougouri, Burkina Faso (A. Bationo, personal communication)

major portion of their harvest in order to increase their profit. Organized farmer groups have better access to post-harvest credit provided on the basis of stored grain as collateral. Incomes of farmers in Niger accessing the *warrantage* system increased by 52 to 134% as a result of the improved farm produce prices. Through the *warrantage* system farmers have greater access to inputs, particularly fertilizer and pesticides, leading to higher sustained yields. In Niger, the adoption of the micro-dosing technologies was rapid. In just 3 years, a total of about 5,000 farm households in 20 pilot locations applied a suite of improved agricultural technologies, doubling their food supply and increasing farm incomes by over 50% (Tabo *et al.* 2006). Over the years, the number of farmers adopting the micro-dose technology has continued to grow, increasing the potential for meeting the food needs of the population in the Sahel.

The potential of micro-dosing is enormous. Even if it had been employed by just a quarter of Niger's farmers in 2005, it is estimated an additional 275,000 tons of millet grain would have been produced sufficient to eliminate the 2005 shortfall. Indeed, the economics of fertilizer micro-dosing are impressive at both the field and national scales. The devastating Niger famine in 2005 was caused by a food shortfall of only 11%. This food deficit could also have been avoided if only one-quarter of the country's farmers had applied micro-dosed fertilizer the previous year. This action would have cost only US $20 million but would have saved donors US $80 million in emergency food aid and affected consumers by US $70 million in lower food costs, to say nothing of the human suffering alleviated.

There still remain millions of farm families across the West African Sahel that are unaware of fertilizer micro-dosing or *warrantage* grain storage and marketing. Farmers are most willing to adopt what they see in the field and when fertilizer and grain prices favor profitability (Fujisaka 1994). To date, fertilizer micro-dosing has reintroduced fertilizer use in Zimbabwe, Mozambique and South Africa in the southern part of Africa and in Niger, Mali and Burkina Faso in West Africa. One great advantage to this practice is that it does not increase labor requirements and the technology is applicable within a range of land conditions including sandy, severely degraded and crusted soils. Its effect on production is readily recognized by farmers, especially when incorporated or mulched organic inputs are also applied. With a fuller suite of improved soil fertility and water conservation practices available to them, African farmers in semi-arid climates are better able to innovate and adjust their management to local and variable seasonal conditions.

Chapter 8. ISFM practice in savannas and woodlands

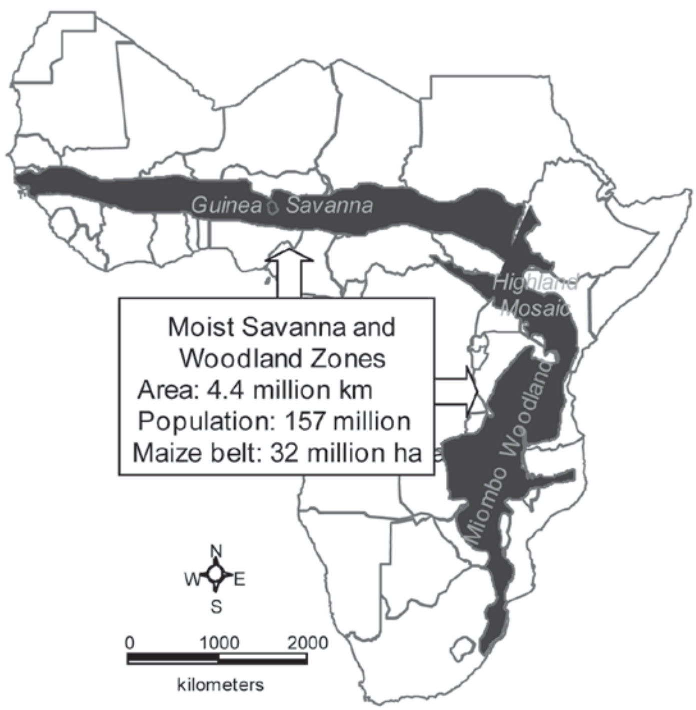


Figure 8.1. Coverage of the moist savanna and woodland zone that is suitable to maize-legume cropping includes the Guinea Savanna of West Africa, the Miombo Woodlands of Southern Africa and East Africa's Highland Mosaic.

African savannas and woodlands are semi- and sub-humid areas well suited to intensified cereal and legume production. These lands may be separated into three broad vegetation zones (Figure 8.1), the Guinea savanna of West and Central Africa, the Miombo and associated dry woodlands of Southern and coastal East Africa and the Highland Mosaic of East Africa, including parts of Ethiopia (White 1983). From the agricultural perspective, these lands may also be separated into areas with a single growing season (monomodal precipitation) or those with two seasons (bimodal precipitation). The moist savanna and woodland zone covers 4.4 million km^2, 32 million ha of which has been converted into maize cropland, and supports a human population of approximately 157 million.

Because this zone extends from well North and South of the equator, and crosses lowlands, plateaus and mountainous regions, large differences in climate, soil and natural vegetation exist. The Guinea savanna is a transition zone between the Sudanese drier savanna and the humid Guineo-Congolian forest that covers about 1.2 million km^2 (White 1983). It stretches from coastal West Africa to Uganda and the Ethiopian Highlands, has well defined wet and dry seasons and consists of secondary grassland and cultivated areas as its original forests have mostly been destroyed by fire, wood harvest and conversion to agriculture. The southern area of this production zone is dominated by dry woodlands (Figure 8.1) and corresponds to the Southern African Plateau, a prominent geographic feature that lies between 900 and 2500 m in elevation with large, flat areas. This area has pronounced monomodal rainfall with large areas of secondary grassland and lands converted to agriculture. Episodic drought occurs in Southern Africa with disastrous human impacts.

In the center of this zone are the East African Highlands and the adjacent drier forests and brushlands. The East African Highlands are part of the larger Afromontane Archipelago emerging in Ethiopia, Kenya and northern Tanzania, in eastern Congo and West Uganda and northern Malawi and adjacent areas (White 1983). These highlands generally have rich soils and abundant, well distributed rainfall. The original vegetation varies with elevation and includes alpine grasslands, mixed rain forest, single-dominant stands of conifers, bamboo, dry transitional forest and evergreen bushland. Presently, these highlands host many coffee, tea and horticultural operations as well as mixed enterprise and cereal-based small-scale farms. In some cases, these lands have become nutrient-depleted (Buresch *et al.* 1997) and subject to generational land division that has resulted in densely populated, near peri-urban settlement (Woomer *et al.* 1997).

Population pressure has resulted in maize-based cultivation of adjacent drier areas that are often subject to drought (RoK 2001).

Maize is the most important enterprise throughout this zone but a wide variety of other annual and perennial crops are also cultivated, owing in large part to the favorable combination of radiation and rainfall. National average maize yields, however, remain quite low, ranging from 900 to 1800 kg ha^{-1}, in large part because of the low rates of fertilizer consumption (Table 8.1). Other cereals include sorghum, finger millet, upland rice and, in milder climates, wheat and barley. Adapted field legumes include bean, cowpea, groundnut, soybean, pigeon pea, grams, and many other pulses, including those of African origin such as Bambara groundnut (*Vigna subterranea*). A wide variety of cash crops and their integration with tree and livestock enterprises results in many opportunities for refining the flow of organic resources and raising farmers' capacity for investment, value addition and commodity marketing. Land preparation is generally performed by hand digging or animal traction, followed by planting traditional and improved crop varieties. The amounts of fertilizers applied throughout this zone vary greatly depending upon country (Table 8.1), availability of farm inputs and access to commodity markets. Within a single community, very large differences in household resource endowment exist, with poorer farms occupying smaller land holdings, owning fewer livestock and oriented more toward household food production (Shepherd and Soule 1998). Two other factors greatly influence cereal cropping in this zone, the infestation and spread of parasitic striga (*Striga asiatica* and *S. hemonthecia)* into cropland (Woomer *et al.* 2005, 2008), and the formation of strong soil fertility gradients with land around the farm homestead retaining or increasing in soil fertility at the expense of other distal, degrading fields (Vanlauwe *et al.* 2006).

Table 8.1. Fertilizer consumption and maize production in selected African countries (based on FAOSTAT 2004).

Region	fertilizer consumption		maize production	
country	average	total	area	yield
	kg ha^{-1}	MT	x 1000 ha	kg ha^{-1}
East Africa				
Ethiopia	13	147,475	1,712	1,744
Kenya	29	146,151	1,547	1,564
Uganda	1	7,248	652	1,781
Southern Africa				
Malawi	39	90,094	1,457	1,296
Mozambique	5	21,367	1,183	898
Zambia	8	44,320	476	1,454
Zimbabwe	43	142,500	1,319	1,022
West Africa				
Ghana	4	24,648	783	1,421
Nigeria	6	191,567	4,177	1,090
Burkina Faso	3	12,422	317	1,768

This zone has the greatest potential to serve as the much needed bread basket of sub-Saharan Africa. The natural landscape is readily converted to agriculture, the precipitation pattern and amount suits cereal production and ripening, the soils often have favorable physical characteristics and transportation and community infrastructure and commodity markets are among the best in Africa. Two related factors, however, reduce this potential; rapidly growing populations have resulted in a multitude of small farms (Woomer *et al.* 1997; RoK 2001), and decades of continuous cropping has led to severe soil degradation (Hartemink 2003; Smaling *et al.* 1997).

For purposes of simplification, this zone also includes highland areas belonging to the Afro-montane Zone with its cool to mild climate, more reliable and well distributed rainfall (White 1983) and relatively young, fertile soils (FAO 1977). These lands were particularly targeted by white settlers during Africa's colonial periods and converted into coffee, tea, tree and other plantations. Following independence, many of the plantations remained intact, and are managed at commercial scales, including continued strong reliance upon purchased farm inputs. In other cases, large holdings were sub-divided and converted into mixed enterprise smaller-scale farms where a variety of domestic animals and cash and household food crops are raised. These farms offer particular promise to develop sustainable land management strategies given the diversity of organic resources, marketing opportunities and investment potential available to these households.

Current soil fertility management practices

Virtually all of the soil fertility management interventions related to strategic application of mineral fertilizers, increasing biological nitrogen fixation, improving nutrient recycling and promoting crop livestock interactions are available to small-scale farmers in this zone (see Chapter 6). The capacity to invest in external sources of nutrients, such as fertilizers and agro-minerals is closely related to cash cropping and market access. Conversely, households that are not selling produce or animal products find it difficult to afford mineral fertilizers, even at rates well below recommended levels (Hartemink 2003).

Households have three basic options to increase biological nitrogen fixation, 1) inoculation of legumes in locations where indigenous rhizobia are deficient, 2) increasing the coverage of nitrogen-fixing legumes within their farms and 3) substituting legumes with stronger capacities of BNF. In many cases, increasing BNF involves the adoption of new legume crops and enterprises. Maize-legume intercropping is a near ubiquitous practice throughout East Africa, although controversy surrounds the comparative benefits from farmers' common choice of bean (see Chapter 6). Intercropping maize with groundnut and pigeon pea are proven successes in this area that are covered in fuller detail later in this chapter.

In many cases, it is possible for farmers to improve upon both the availability of organic resources and the efficiency of their use. Increasing cereal yields directly improves the availability of crop residues both above- and below-ground. Farmers in more densely populated settings often find it necessary to mark farm boundaries with trees or shrubs or to establish impenetrable hedgerows, and these plants can serve as sources of both soil inputs and animal feed. Limited access to land may be offset by greater availability of labor, permitting operations such as intensive pruning or compost-making. Some practices such as natural and improved fallows, rotational paddock grazing and increasing herd size obviously become restricted as pressure upon land intensifies. These shortcomings may be offset by intensifying animal enterprises including improving animal breeds, and diets, increasing the efficiency of waste recovery and better handling, processing and storing manures and composts. It is not the lack of soil fertility options that are available to small-scale farmers in maize-based croplands, but rather the manner in which limited available resources are combined and to which enterprises they become directed that presents the greatest challenge to ISFM in this zone.

ISFM best practices

Two large opportunities exist to strengthen soil fertility management in the maize-based cropping systems of moist savanna and woodland zone; the intensification of legume cultivation and strengthened interaction between crop and livestock enterprises. Legume enterprises may be developed as either intercrops or in rotation with cereals, with different legumes assuming importance within various climatic and socio-economic settings (Yusuf *et al.* 2009). New opportunities for favorable interactions between crops and livestock are driven in large part by increased confinement of livestock and small animals resulting in greater control of their feeding and improved access and handling of their wastes.

Refinements to maize-legume intercropping. Simple innovations in maize-legume intercropping permit farmers to grow a wider range of food legumes as under-storey intercrops with maize. Maize may be planted at its recommended population, but every-other row is shifted to provide a wider alternate inter-row to the legume or strip-cropped by lowering maize populations but maintaining similar yields. Either approach permits more productive intercropping with groundnut, green gram, soybean and other higher-value food legumes that are not otherwise intercropped with maize because of excessive shading (Woomer *et al.* 2004) An innovative intercropping approach known as for its founding project MBILI (Managing Better Interactions for Legume Intercrops) was compared to other recommended soil fertility management systems on 120 farms in West Kenya over three consecutive growing seasons. These other managements included the current recommendation by Ministry of Agriculture (MoA) agricultural extension (KARI 1994), nutrient replenishment with Tanzanian rock P (Buresh *et al.* 1997) and application of fortified manure compost (N'dungu *et al.* 2003). MBILI resulted in the highest maize yields, largest net return, most favorable benefit to cost ratio and best fertilizer use efficiency (see Chapter 1, Table 1.4). Similar advantages to legume intercropping were obtained when sorghum was examined under the MBILI system in Uganda (Owuor *et al.* 2002). These results illustrate how simple innovations to intercropping can complement other soil fertility management technologies.

Not only does MBILI result in improved crop yields and increased profits, but it also serves as an entry point for several practices relating to ISFM. These practices include improved fertilizer use efficiency, increased BNF, partial substitution of pre-plant mineral fertilizers with composted manure, greater returns from inexpensive agro-minerals and better timing and placement of top-dressed mineral nitrogen, each of which further increases the benefits from MBILI intercropping (Figure 8.2).

Farmers who observe innovative intercropping systems or have access to extension literature describing these techniques can readily establish the staggered intercrop and observe its effects. Farmers quickly develop attachments for draft animals to facilitate field operations. For example, only five years after its development, MBILI was practiced by 16% of independently surveyed households in West Kenya. This success is due in large part to MBILI being equally accessible to best and least resource endowed households but households ranked as resource poor adopt MBILI three times more rapidly than other farmers. In addition, MBILI permits cultivation of legumes that suppress *Striga hermonthica* such as *Lablab* and *Desmodium* (Woomer *et al.* 2005, 2008). Extension materials describing MBILI are available (Tungani *et al.* 2002) and have been translated into native languages, setting a positive example for other efforts aimed at intensifying cereal-legume enterprises.

Innovations in cereal-legume intercropping stimulate both community-based and commercial seed production through greater demand for improved varieties of legume seed such as disease-resistant groundnuts and promiscuously-nodulating soybean. Innovative intercropping also complements the promotion of mineral fertilizer among Africa's small-scale farmers and it is ready for immediate

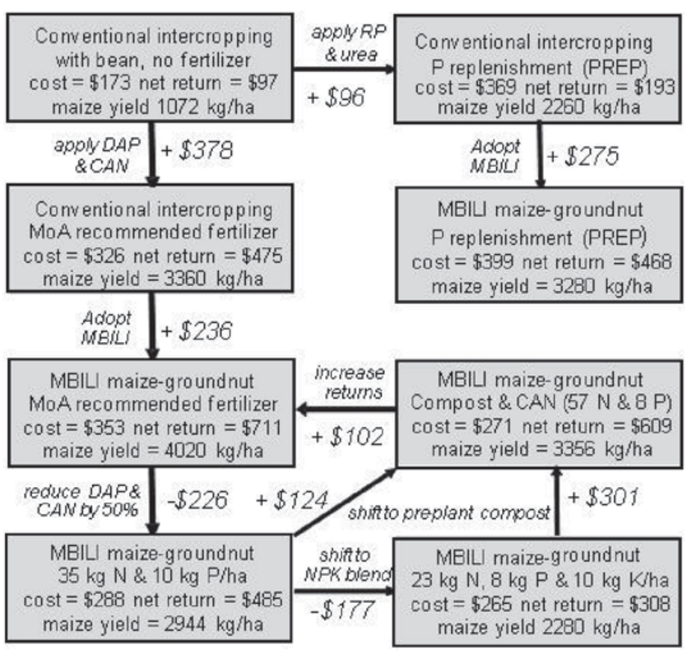


Figure 8.2. Soil fertility management options examined in Vihiga, Kenya during the 2004 long rains. MBILI is a locally developed maize-legume intercropping arrangement with paired, staggered rows.

deployment for wider use by cereal producers in both humid and semi-humid areas. Greater understanding and adjustments are required, however, before this system can be recommended in semi-arid areas.

Cowpea intercropping in West Africa. In the northern part of the dry savanna in West Africa, cropping is cereal-based with sorghum and millet dominant. Intercropping with grain legumes is widely practiced with cowpea and groundnut the most common legumes. Until the late 1980s, cowpea breeding at IITA focused upon the development of new varieties with high grain yield. Some farmers adopted these varieties reluctantly, provided they had access to the necessary inputs, particularly insecticides. For the majority of the farmers in the dry savanna, this was not the case. The limited adoption of these varieties and the increased recognition of the importance of cowpea fodder for animal feeding led to a redirection of IITA's breeding strategy. When seeking to address the opportunities posed by the intensification of crop-livestock systems in the dry savannas, it was apparent that a key component should be increased cowpea biomass. The aim became to develop a dual-purpose cowpea that produced good quantities of both grain and fodder with minimum insecticide requirement. These crops provide grain essential for family food and income, as well as crop residues for livestock feed. Livestock in turn make an important contribution to crop production through manure and traction. Intercropping with a dense growth of cowpea reduces striga and its seedbank. There is a complex set of interactions between the biophysical, economic, social, and policy environments that influence farmers' decisions in these areas. As a result, several institutions conducted joint research on Best-Bet (BB) technological options for cowpea in West Africa cropping systems in over several years (Tarawali *et al*. 2001).

Three Best-Bet treatments were implemented on farmers' fields for four years in Nigeria, Niger, and Mali. These treatments were: 1) BB+: improved cowpea and sorghum, minimum inputs of fertilizer to sorghum and insecticide to cowpea; row arrangement 2 rows sorghum and 4 rows cowpea, livestock feeding with residues from the trial plots, and return of the manure at the start of the cropping season; 2) BB–: same as for BB+ but with local sorghum and 3) local farmers cowpea–sorghum intercrop. It was recognized that the Best-Bet options would flexibly differ among locations within the dry savanna, depending on the dominant management practices. Results of the livestock integration work show that the quantities of grain and fodder produced in the BB managements with dual-purpose cowpea and modest external inputs were greater than those in the farmers' practice (Tarawali *et al*. 2001). The most dramatic difference was for cowpea grain where BB+ yielded about 16 times more than the farmers' practice. Fodder yielded increased five-fold over farmers' practice. Livestock fed on the BB+ residues gained significantly more weight over a 16-week feeding period. Analysis of the nutrient dynamics shows strong positive balances for N and P for the Best Bet managements. At the end of the 1999 crop season, the BB+ had a net positive balance of 41 kg N ha^{-1} and 14 kg P ha^{-1} compared to a negative balance of -28 kg N ha^{-1} and 0. 7 kg P ha^{-1} for the farmers' practice. An economic evaluation was conducted to compare the costs, returns and profits among the two Best–Bet treatments. Annual total revenue was about US $300 ha^{-1} for BB+ compared to US $155 for farmers' practice. BB+ resulted in nearly four-fold increase in profits (Tarawali *et al*. 2001). The benefit-cost ratio was 1.77 for BB+ compared to 1.26 for farmers' practice. A comparative economic analysis over time also revealed a reduction in production costs for inputs and labor resulting from positive nutrient balances and the farmers' mastering new skills with time.

Pigeon pea intercropping in Southern Africa. Intercropping maize with dual-purpose pigeon pea, combined with adjusted agronomic practices and judicious fertilizer use, has successfully improved land productivity in Southern Africa. Both crops are planted at the same time, but early development of pigeon pea is slow, and maize is harvested before the long-duration pigeon pea begins to form substantial biomass. After the maize is harvested, pigeon pea grows for several more months on residual soil moisture, produces a complete canopy cover and yields of up to 1.5 t ha^{-1} of grains. Maize is planted at the same spacing as in the monocrop, and yields of maize planted as an intercrop are similar to those of sole maize. Combining pigeon pea and maize reduces N and P fertilizer needs in subsequent years (Sogbedji *et al.* 2006). Inputs of N through fallen pigeon pea leaves contributes 75-90 kg N ha^{-1} which substantially benefits a following maize crop (Sakala *et al.* 2000). Pigeon pea is also capable of accessing scarce soil soluble P and can efficiently utilize residual P remaining in the soil from fertilizer applied to maize (Bahl and Pasricha 1998). In addition, pigeon pea leads to significant reductions in pest and disease damage (Sileshi and Mafongoya 2003; Chabi-Olaye *et al.* 2005). Pigeon pea-maize intercropping is a common farmers' practice in southern Malawi and parts of Mozambique and Tanzania but is possible only where some rains occur during the extended dry season. Pigeon pea is also used in intercropping in the derived savanna of West Africa, particularly in Benin and southern Nigeria.

The success of this system is related to an efficient extension program linking diverse stakeholders, from farmers and researchers to potential buyers and input suppliers (Snapp 2004). A collaborative team approach across industry, NGOs and government services has facilitated farmer access to inputs, new cultivars and training in improved crop management and post-harvest techniques. As a result of the technologies and dissemination approaches, intercropping maize and pigeon pea is becoming a common farmers' practice in Southern Africa. This system also offers opportunity for accessing better markets and prices (Jones *et al.* 2002), including export opportunities to Europe and India, the world's largest consumers of pigeon pea. Through linkage to millers and guaranteed good grain quality, the export market grew rapidly with 40,000 tons of pigeon pea shipped from central Tanzania in 2002.

Cereal-legume rotation. A key entry point for addressing the problems of soil deterioration has been the greater availability of inorganic and organic inputs and more resilient and adoptable germplasm of both cereals and legumes. Adapting improved germplasm to soil problems has lead to sustainable cropping that serves as a starting point for transforming the market orientation of small-scale farmers. Along these lines, researchers pioneered sustainable maize–soybean rotations that combine significant BNF while suppressing striga, a pernicious plant parasite of cereals throughout the savanna zone (Woomer 2008). This cropping system also replenishes soil nutrients and improves the availability of organic resources. In addition, the legume varieties have traits that are appreciated by farmers, such as high yields of both grain and fodder, pest and disease resistance and promiscuous root nodulation by rhizobia that greatly improve farm income by 50–70% compared to continuous maize cultivation. The strong commercial demand for soybean worldwide further justifies targeted investment into this production system.

Soybean in West Africa. During the last two decades, IITA and its partners developed and implemented sustainable grain legume-cereal rotations. Substantial gains were realized through the adoption of promiscuously nodulating soybean varieties during the early 1990s (Sanginga *et al.* 1997). These varieties produce high yields and are also multi-purpose in terms of leafy biomass production available to livestock and as an organic input to soil (Sanginga *et al.* 2001a). These soybean lines symbiose with indigenous soil rhizobia as well as exotic inoculant strains, greatly facilitating nitrogen fixation under smallholder farming conditions. Adoption of these new varieties was initially slow but gained rapid momentum as they became more widely known to farmers with the released varieties later adopted by 75% of male and 62% of women farmers by 1996 (Sanginga *et al.* 1999). This adoption occured even in the absence of an efficient seed distribution system, in large part because the crop is self-pollinated allowing farmers to save their own seed for planting and the cultivation of promiscuous increased by 228% over only three years. The second and third generation adopters were generally younger men and women less than 40 years old (Sanginga *et al.* 1999). Adoption was further promoted through inherited resistance to Frogeye Leaf Spot. More recently developed varieties demonstrate even greater promiscuity and are likely to prove more attractive to smallholders in the future.

The promiscuous soybean and the dual-purpose cowpea lines that are now available to farmers in West Africa produce about 2.5 t of grain and 2.5 to 4 t of forage per ha and there is every indication that further progress can be made. They fix between 44 and 103 kg N ha^{-1} and have a positive N balance of 43 kg N ha^{-1}. Growing maize after soybean improves grain yield 1.2- to 2.3-fold. Combining cowpea or soybean residue with 45 kg urea-N ha^{-1} provides maize yields similar to the recommended rate of 90 kg urea-N ha^{-1} on even the poorest fields (Sanginga *et al.* 2001a). Costs and benefits of treatment of a maize rotation with an improved promiscuous soybean can provide a net benefit of US $1450 over two seasons (Sanginga *et al.* 2001a).

Widespread adoption of maize-legume rotation in West Africa was supported through several additional mechanisms including farmer collective action, development of underlying value-added cottage industries, product development and branding, information exchange and development of rural savings and banking systems (Clark *et al.* 2003). Extension efforts for creating awareness in home utilization techniques and stimulating small income-generating businesses has resulted in the improved wellbeing of millions of people in both urban and rural areas. The success of soybean in Nigeria was also related to training in household utilization of soybeans to overcome the off-flavor if they are improperly cooked. The presence of small industries for soybean processing provided a ready supply of soybean products, and stimulated their production and consumption. Partnerships were formed with government, voluntary agencies and NGOs to incorporate soybean utilization into their activities. Hospitals were also involved and several childrens' foods were prepared from soybean.

Soybean in Zimbabwe. Soybean was promoted in Zimbabwe as a smallholder crop in the 1980's using specifically-nodulating varieties requiring inoculation. This effort floundered, largely because smallholders experienced difficulties in accessing seed and inoculants. A later, community focused initiative better assisted smallholders to grow soybean with rhizobial inoculants, defying a long-held belief that soybean was an inappropriate crop for their cropping systems (Mpepereki *et al.* 2000). Special training was offered to participating farmers on the use of inoculants that were originally produced for the commercial agriculture sector (Marufu *et al.* 1995).

This soybean program linked smallholders to markets and led to rapid expansion of only 50 farmers in 1996 to an estimated 10,000 farmers three years later. Although the initial aim was to promote the promiscuously-nodulating Magoye soybean variety, the program has largely relied on assisting farmers to access seed of specifically-nodulating varieties as well, together with careful extension on the use of inoculants. This modification was necessary because there was insufficient seed production of the promiscuous varieties to meet the rapid increase in farmers' demand. As a result farmers proved keen to grow both the specifically-nodulating varieties, because of their greater yield potential as a cash crop, and the dual purpose promiscuous that does not depend on access to inoculants. Farmers also recognize the greater potential of the promiscuous varieties for fodder and soil fertility improvement (Mpepereki *et al.* 2000). Local extension staff provided training in local processing of soybean for a variety of uses including mixing with maize flour to produce protein fortified porridge for children, baking soya bread and pressing soya milk.

Crop-livestock interactions. Soil fertility in the moist savannas has long been associated with grass productivity and nutrient recycling through animal grazing. Prior to human domination, these lands supported the largest populations of grazing wildlife in the world. This wildlife was partially displaced by livestock of migratory pastoralists who, were in turn replaced by agriculturalists practicing shifting cultivation and grazed fallows (Boonman 1993). As human populations increased, less land was available for pasture and grazed fallows, and farmers adjusted to changing circumstances by confining their livestock and taking greater control over their feeding. Farmers are able to compensate for diminished opportunity for grazing by feeding confined livestock crop residues, fodder grasses and prunings of trees and shrubs, and then to collect and apply animal wastes in a manner that tightens nutrient recycling (Lekasi 2001b).

Several technologies have developed around the collection, processing and application of livestock wastes, particularly dairy cattle and poultry. Cattle stalls may be constructed in a manner that separates urine and manure so that these two products may be handled and applied differently. Urine is best applied to perennial crops immediately after collection as its nitrogen is subject to volatilization loss (Lekasi *et al.* 1998). Manures on the other hand can be heaped and composted for use during the next cycle of cropland preparation. Keys to more efficient manure storage include recessing them into shallow pits and covering the heaps to conserve nutrients. Once protected from nutrient loss and allowed to compost, manure quality may be further improved by providing livestock with feed concentrates, constructing a sloped concrete floor in the stall, adding and collecting bedding materials from the stalls, applying ash, rock phosphate or mineral fertilizers (N'dungu *et al.* 2003) or by incorporating green manures into the heap (Lekasi *et al.* 2001a).

One example of how an important endemic grass may remain useful throughout the transition from pastoralism through intensive agricultural settlement may be found in the case of napier grass (*Penisetum purpureum*). This species is a large bunch grass that is native to sub-humid East Africa but also occurs in Central, Southern and West Africa (Boonman 1993). It was cultivated during traditional times in the Kingdom of Buganda as an improved fallow and a source of mulch and grazed by wildlife and cattle, including on the ranches of early European settlers. A legume understory is more compatible with napier grass when grazed owing to less competition from the tall stems and thick litter layer. But as farm size decreased and need for sources of cattle feed grew, smallholders cultivated this grass in dense, intensively managed hedgerows and fodder banks that resulted in carrying capacities that are 40% greater than under grazing. Moreover, these zero grazing systems resulted in 243% greater economic returns than grazing, largely as the result of labor intensification, and permitted the adoption of other cost effective innovations, particularly chopping and blending of napier grass with other fodder sources, including legumes (Boonman 1993). The greater control of livestock within small-scale farming systems provides opportunities for improved nutrient recycling of domestic animal manures that may be directed and fine-tuned through ISFM.

Three developmental lessons learned in maize-based systems

Legume varieties are available for the special farming needs of smallholders. To a large extent, field legume production in Africa is dominated by the cultivation of low-yielding, traditional varieties that agricultural planners seek to replace with higher-yielding, determinate varieties. This approach does not take into account the more complex needs of Africa's small-scale farmers for more and better quality crop residues, livestock feed and off-season sources of food. The recent availability of less-determinate and promiscuously-nodulating legume varieties represents a technical breakthrough in that a single legume crop can now meet several household needs. For example, many legumes may be harvested and consumed or sold at the green pod stage, and the plentiful foliage fed to livestock. Farmers can then allow the last grains to mature for home processing, marketing or the following season's planting. The challenge is to develop seed systems that can rapidly multiply and distribute the most desirable legume seeds and their accompanying technologies to farmers attracted to improved cereal-legume intercropping and rotation.

Stronger public-private partnership is essential. Public–private partnerships in agriculture are particularly effective in conducting applied research in ISFM technologies, refining new farm input products and deploying these products for the benefit of small-scale consumers. Public–private partnerships are essemtially broad-based collaborations that jointly plan and implement

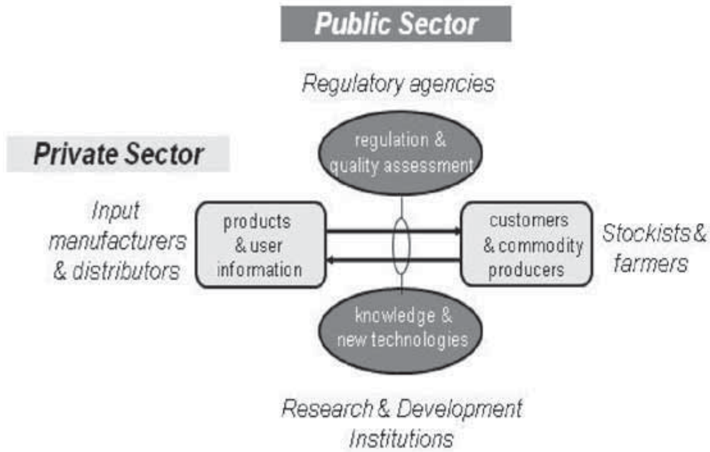


Figure 8.3. Public-private partnership is necessary to provide quality ISFM products to small-scale farmers.

activities toward mutually agreed-upon objectives while sharing the costs, risks, and benefits incurred in the process (Spielman *et al.* 2007). This sort of collaboration can overcome many of the restrictions imposed by weak markets, institutional constraints, and systemic shortcomings in agricultural research by building on complementarities. Take for example the well established criteria for successful supply of improved legume seed and rhizobial inoculants. Seed and inoculants are best produced by the private sector at a commercial scale and marketed to farmers with accompanying information (Figure 8.3). Farmers must provide feedback to commercial suppliers in terms of varietal suitability. At the same time, it is important that the public sector supplies essential regulatory and germplasm services. Regulation of seeds and inoculants must not be restrictive, but at the same time, their quality must be assured. Public sector scientists have an important role to play by identifying superior legume varieties and rhizobia, matching them together and exploring new planting and inoculation technologies. Public institutions that assume too much responsibility for product development such as seed multiplication, strain identification and preservation, inoculant manufacture, quality assurance, seed and inoculant marketing and grassroots extension risk performing all of these tasks poorly for lack of competition and peer support. At its infancy, these services may be conducted by public institutions as a means to explore production technologies, assess efficacy in the field and improve farmer awareness, but it is important that this production be handed over to commercial interests once they become economically viable.

Proven new technologies must be actively promoted. It is insufficient for advanced institutes or national research organizations to simply develop improved ISFM technologies such as new legume varieties and inoculation procedures, and then expect farmers and agro-entrepreneurs to spontaneously adopt them. Before farm households will adopt new grain legumes, home and community-based processing must be demonstrated to stimulate local consumption. Active extension and farmer training on agronomy and inoculum use are also required to stimulate farmers' interest in new crops. Fair commodity markets must be opened to farmers to encourage them to produce surpluses. The suitability of legume foliage as a high quality feed, or the benefits of BNF and crop residues must be explained to farmers in terms they understand. The most effective information exchange occurs between farmers that have successfully adopted a technology and their neighbors who wish to do so, and means must be found to empower the first generation of early cereal-legume innovators to stimulate the process of farmer-to-farmer technology transfer.

Chapter 9: ISFM practices in the humid forest zone

The main area of the humid forest zone extends as a broad band North and South of the equator from the Atlantic seaboard of Central and West Africa westwards to the mountains of the western Great Rift Valley. The natural vegetation at the core of this zone consists of Guino-Congolean rainforest with semi-evergreen, transitional forests toward drier zones to the North (Sudanean) and south (Zambezian). As a whole, these forests occupy approximately 5.8 million km^2 and support a population of 163 million (Figure 9.1). Within the humid forest areas of West Africa and in the Congo Basin, the elevation ranges from sea level to 1000 meters, and most of this area receives between 1600 to 2000 mm of rainfall per year. Despite this rainfall, parts of this zone experience an annual dry season of up to three months and rainfall exhibits a weak bimodal pattern along the West African coast. In areas with semi-evergreen, transitional forest, rainfall may be as low as 1200 mm. The humid forest zone is rich in plant biodiversity, with over 8000 species in the Guino-Congolean Center of Endemism (White 1983). The original forest contains trees between 30 and 60 meters high and is rich in climbers and epiphytes, but few terrestrial herbs. Presently, most of this zone outside of forest reserves is occupied by secondary forest following disturbance by fire, cultivation and excessive logging. Older secondary forests reach a height of 35 meters and are composed of different and less diverse plants. In addition, edaphic grasslands exist within waterlogged or frequently burned areas.

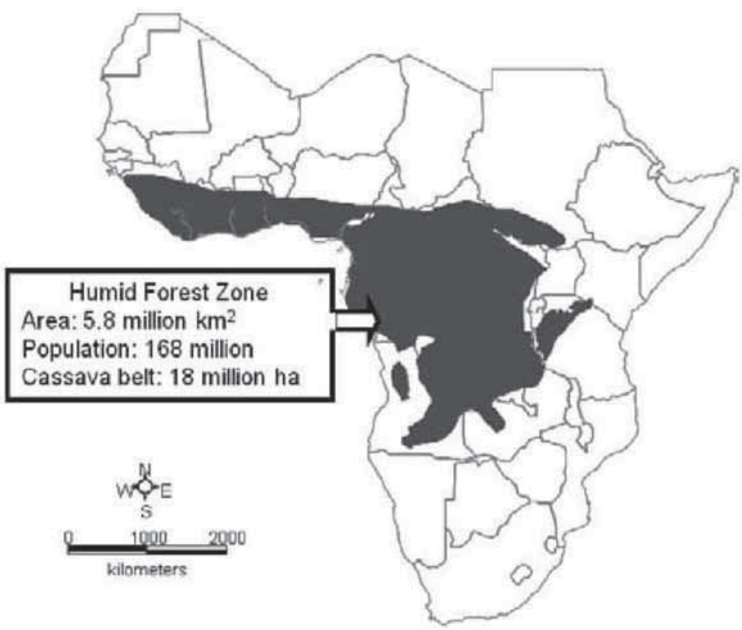


Figure 9.1. Distribution of the humid forest zone of Central and West Africa, an area largely covered by primary and secondary forest, perennial crops, natural fallow and shifting cultivation.

The soils of the Central African Basin are dominated by highly weathered, acidic Ferralsols with low base saturation and few nutrient reserves. Among these soils, suitability for perennial cropping in coffee, oil palm and cocoa is determined by soil texture, with >30% clay considered a critical threshold for establishing commercial plantations (FAO 1977). In the highest rainfall area, Orthic and Plinthic Ferralsols occur with extremely low inherent soil fertility and surface features unfavorable for field cropping. In lower lying, poorly drained areas, Gleysols and Histosols dominate where swamp forest is being converted to wetland rice. Drier areas within this zone contain Luvisols, Acrisols, and Cambisols and those adjacent to the western Rift Valley are affected by Andosols resulting from recent volcanism (FAO 1977).

Nutrient allocation, redistribution and loss

Nutrients within tropical forests are differentially allocated between biomass and soil pools (Table 9.1). Most nitrogen remains in the soil organic matter as forms that are not readily available (Woomer and Swift 1994) but substantial amounts are assimilated and recycled by plants. In contrast, most system phosphorus is contained within biomass. A large proportion of base nutrients (K, Ca and Mg) may also be present within plants, particularly in highly weathered, acidic soils (Juo and Manu 1994). Disturbance of the primary forests is driven by two factors, commercial logging and shifting cultivation, often in conjunction. Slash-and-burn serves as an expedient mechanism to mobilize and redirect nutrient stocks to the soil, particularly P and the nutrient bases (Table 9.2). Nitrogen is subject to loss during burning (Nye and Greenland 1964) but its availability is improved through the decomposition of root biomass a few weeks after this disturbance (Araki 1993). The stability of soil organic matter throughout the slash-and-burn cycle serves to protect soil nitrogen from loss, assuming that it is not eroded as a result of land clearing (Woomer *et al.* 2000) (Figure 9.2).

In the past, slash-and-burn was conducted at a low intensity with accompanying long fallow intervals leading to the establishment of secondary forest. As land availability decreases, so too does the fallow interval until the landscape becomes dominated by mixed cropping systems and bush fallow (Nye and Greenland 1960). The hypothetical relationship between fallow interval, soil fertility renewal and cropping

Table 9.1. Nutrients in biomass and soils of secondary forests in the humid zone of Africa (after Juo and Manu 1994). MAR signifies mean annual rainfall.

site & characteristics	nutrients within secondary forest N	P	K	Ca & Mg
	---------------- kg ha^{-1}			-------------------
Kade, Ghana (Luvisol) MAR 1650 mm				
biomass	1837	126	822	2880
soil	4608	12	652	2953
Yangambi, DR Congo (Ferralsol) MAR 1854 mm				
biomass	561	73	406	563
soil	2248	19	380	153
Kasama, Zambia (Ferralsol) MAR 1200 mm				
biomass	1653	322	300	na
soil	4283	10	133	na

Table 9.2. Changes in selected soil properties before and after slash-and-burn (after Juo and Manu 1994 and Araki 1993). MAR signifies mean annual rainfall

site & characteristics	nutrients within soil NH_4	P	K	Ca & Mg
	---- mg kg^{-1} ----		--- meq 100 g^{-1} ---	
Kade, Ghana (Alfisol) MAR 1650 mm				
before burning	na	9.8	0.4	6.9
after burning	na	30.0	2.1	20.6
Ibadan, Nigeria (Luvisol) MAR 1200 mm				
before burning	na	4.7	0.3	7.5
after burning	na	20.7	1.0	9.4
Mpika, Zambia (Ferralsol) MAR 1100 mm				
before burning	4.1	na	0.1	4.4
after burning	23.7	na	0.7	7.0

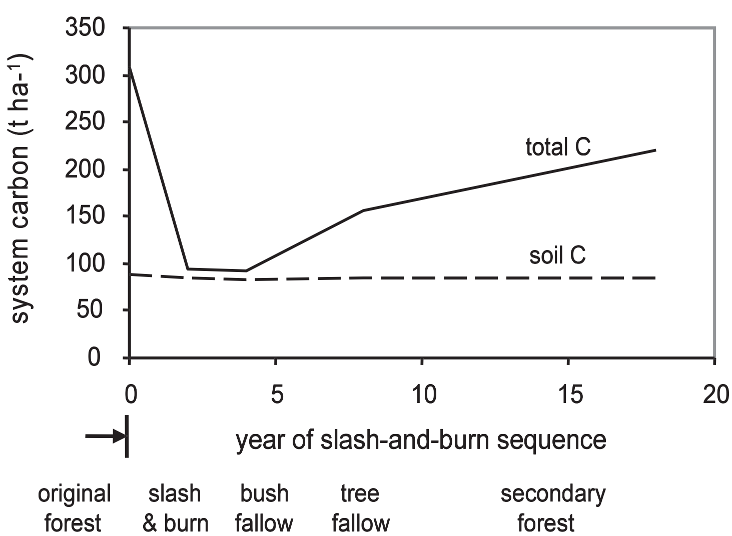


Figure 9.2. Carbon dynamics in slash-and-burn systems in southern Cameroon (after Kotto-Same *et al.* 1997).

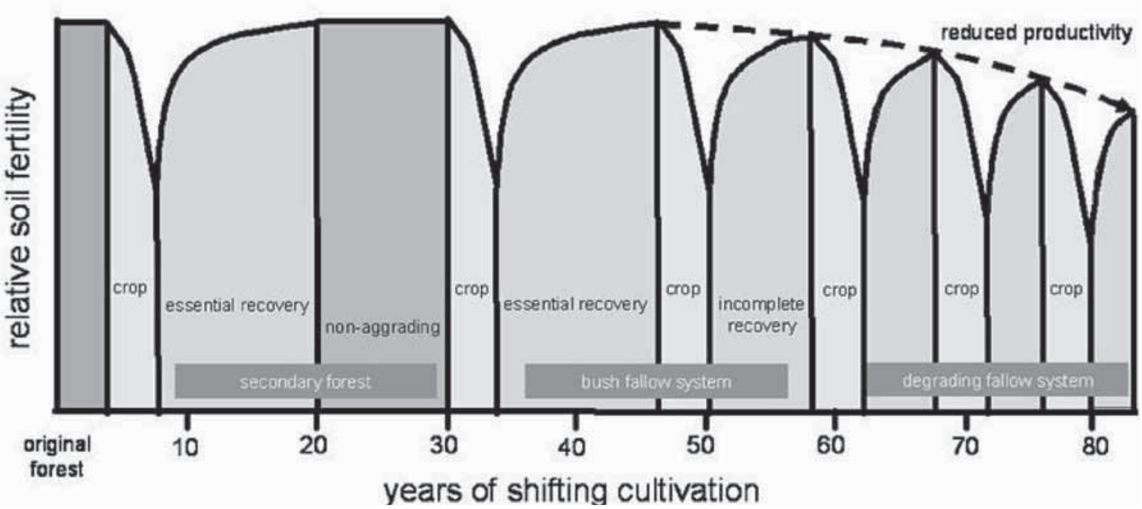


Figure 9.3. Hypothetical relationship between fallow interval, soil fertility renewal and system productivity as land use changes from slash-and-burn to bush fallow and degrading bush fallow systems (after Hauser *et al.* 2006).

system productivity is presented in Figure 9.3. An ideal fallow interval permits soil fertility regeneration to a maximum level for subsequent cropping. As cropping frequency increases, shorter fallow intervals result in incomplete nutrient re-accumulation (Hauser *et al.* 2006). The challenge before land managers is to establish ISFM practices that can sustain land productivity in these soils of low and diminishing soil fertility in absence of extended fallow intervals. Improved fallow by definition permits more rapid nutrient gains and is one means for land managers to cope with decreased land availability under conditions not favoring the use of external nutrient inputs. Hauser *et al.* (2006) suggest that fast-growing herbaceous legumes are better suited as short-term fallows than are trees and shrubs but that the by-products of planted tree fallows, such as poles, charcoal and fruit, can also contribute to farm revenues. From a more holistic perspective, slash-and-burn techniques serve as the land clearing technology of necessity by poor farmers that must ultimately lead to intensive, market-oriented cropping systems if the expectations of rural household are to be met (Harwood 1994). These intensive cropping systems assume the form of mixed enterprise perennial and field crops that require increased levels of management skills, capital, labor and purchased external inputs, including mineral fertilizers that are most efficiently utilized within the context of ISFM.

Farming system characteristics

Traditional agriculture in the forest zone was largely dependent on shifting cultivation, a system that relies upon simple tools and few external inputs but employs sophisticated cropping combinations and sequences (Graves *et al.* 2004). For example, farmers in Central Africa typically cut the original forest before the short dry season, and incompletely burn the felled trees just in advance of the next rains to plant a pioneering intercrop of *egusi* melon (*Citrullus lanatus*) and plantain. *Egusi* melon, used for its nutritious seeds, is harvested after about three months while plantain requires about 18 months before producing a bunch. After plantain is harvested, it continues to compete with encroaching fallow regrowth until the field is cut and burned again after two to four years. By this time, the previously felled logs are dried and the second burn is more complete. At this point, a mixed crop of groundnut, maize, cassava, plantain and local vegetables is established and grown once or twice before the cassava and plantain are harvested and the field abandoned to natural fallow succession. During this cropping sequence, farmers make very efficient use of their labour, felling large trees to knock down smaller ones and planting seeds into holes without tillage, but in the process large amounts of natural and agricultural resources are lost and incompletely re-accumulate during extended fallow intervals.

Shifting cultivation persists in secondary forests and woody savannas where humans remain scarce, however, population growth, land tenure systems and human migration toward larger settlements have forced most fallow intervals to shorten. In many areas of the humid forest zone, cropping periods usually last 1-3 years, followed by increasingly shortened fallow intervals. Laudelout (1990) concluded that these systems remain sustainable under two conditions; cultivation follows a fallow interval of at least twelve years, and population density does not exceed 25 inhabitants per km^2. In most cases, these conditions cannot be met and whatever remnant forests remain must be protected. Gockowski *et al.* (2004) observed that fallow intervals around Yaoundé, Cameroon, with a population of about 75 persons per km^2, have declined to only four years. A detailed evaluation of nutrient inputs, flows and losses in southern Cameroon concluded that nutrient losses from smallholder operations were -70 kg N, -3.1 kg P and -21 kg K per ha per year (Kanmenge *et al.* 2006). In areas where short bush fallows are practiced, the cropping systems comprise mixtures of cassava, banana, plantain and rice. These staple crops tolerate wet climate and less fertile, acidic soils, but respond positively to improvements in soil fertility. The fallow interval offers multiple benefits including soil fertility restoration, weed suppression and disruption of pest and disease cycles, and even short-term field storage of root crops. Fallows may consist of either natural vegetation or planted herbs, shrubs and trees that provide restoration benefits at an accelerated rate. Well managed fallow systems also take cognizance of the need for additional benefits such as fuel wood, food and forage, within the time constraints which are imposed by land use intensification and sound vegetation management.

Planted fallows have been studied in West and Central Africa over several decades. Numerous species and technologies have been tested, mostly on-station but increasingly on-farm (Hauser *et al.* 2006). Alley cropping and technologies using herbaceous cover crops are some of the most promising ones for resource-poor farmers. The use of soil improving legumes as a replacement of the traditional shifting cultivation has been a topic of debate for many years. Opinions range from the conclusion that green manure will never be a significant factor to the viewpoint that agronomic exploitation of BNF through green manuring must become more important in the future. Due to their importance within the humid forest zone, three major food crops with high potential for improved soil fertility management will be examined in the remainder of this Chapter; cassava, rice and banana.

Cassava and its current management

Although cassava is critical to food security of a large number of households in sub-Saharan Africa, relatively little attention, other than the release of pest- and disease-resistant and high yielding varieties, has been paid by the research and development community to better manage its productivity. This is partly related to the perception that cassava yields well under sub-optimal growth conditions and is unlikely to respond to inputs. More recently, however, renewed interest in cassava has resulted from its industrial uses, and enhanced productivity of cassava-based systems has become a more important goal (Howeler 2005). Means to improve cassava production include the use of mineral fertilizer adjusted to specific soil conditions, the use of locally available organic inputs in combination with fertilizer, and the integration of field legume into cassava-based systems.

Cassava is an important food staple in two thirds of the countries in sub-Saharan Africa (Figure 9.4) with an estimated production of 110 million metric tons of fresh roots raised by 100 million farmers on over 12 million hectares (Table 9.3). Over 70% of human population in the Democratic Republic of Congo, 50% in Nigeria, and 30-40% in eight other major producing countries eat cassava at least once a day, a total of about 400 million people or 50% of the continent's inhabitants (Philip *et al.* 2005). Cassava is a versatile crop because of its convertibility into a variety of food, feed and industrial products. Although sub-Saharan Africa produces half of the total world's cassava (Table 9.3), its average yield of 8.9 t ha^{-1} is 50% that of Asia and 66% of Latin America and the Caribbean (Howeler 1991). Cassava production in Africa is predominantly in poor, infertile soils, including marginal lands that cannot support other crops. There is virtually no mineral fertilizer use and nutrients removed as harvest are seldom replenished.

Figure 9.4. Cassava production as a commercial commodity and staple food crop in Africa.

Production is also characterized by inadequate cultural practices, especially the use of poor quality planting material, sub-optimal planting densities, and inadequate weed, pest and disease management. Over 90% of production takes place in small farms. Production has, however, more than tripled in the last four decades, mostly due to increases in area under cultivation rather than in increases in yield (Hillocks 2001). Even where improved varieties are grown, potential yields of 20-35 t ha^{-1} are seldom achieved (Figure 9.5). Average fresh yield levels obtained in without

Table 9.3. Production yield and acreage of cassava in Africa, Asia, Latin America, in selected African countries, and in Thailand, the largest producer in Asia. (FAO-STAT 2004).

Region & Country	Harvested area ('000 ha)		Yield (t ha^{-1})		Production ('000 t)		Annual rate of increase (%)		
	1995	2005	1995	2005	1995	2005	Area	Yield	Production
Africa	10053	12334	8.23	8.88	82775	109575	2.1	0.8	2.8
Angola	500	749	5.1	11.5	2550	8606	4.1	8.5	12.9
Congo DR	2073	1845	8.14	8.11	16870	14974	-1.2	0	-1.2
Ghana	551	784	11.99	12.42	6611	9739	3.6	0.3	4
Kenya	47	60	9.56	10.5	446	630	2.5	1	3.5
Madagascar	348	358	6.89	6.21	2400	2191	0.1	-1	-0.9
Malawi	95	157	3.47	16.56	328	2600	5.2	16.9	23
Mozambique	986	1050	4.24	5.86	4178	6150	0.6	3.3	3.9
Nigeria	2944	4118	10.67	9.27	31404	38179	3.4	-1.4	2
Tanzania	585	670	10.21	10.45	5969	7000	1.4	0.2	1.6
Uganda	332	407	6.7	13.51	2224	5500	2	7.3	9.4
others	1497	1871	6.14	6.76	9194	12656	2.2	1	3.2
Asia	3655	3411	12.63	16.38	46174	55901	-0.6	3.1	2.5
Thailand	1725	985	13.02	17.17	16217	16938	-3.1	2.4	0.3
Latin America	2725	2,911	12.08	12.84	32923	37405	1.9	1.8	3.7

inputs range between 10 and 40 Mt ha^{-1} (Fermont *et al.* 2004). Local varieties yield up to 20 t ha^{-1} less than Cassava Mosaic Disease (CMD)-resistant varieties. The large gap between average farmer and trial yields demonstrate that there is a huge scope for yield improvement. This yield gap can be closed by planting improved, disease-free, high yielding varieties and following better agronomic and integrated pest management (IPM) practices. A combination of pests, diseases, poor cultural practices, and a lack of use of mineral fertilizer contribute to yield losses of over 50% and accounts for the large difference between potential and current yields (Hillocks 2001).

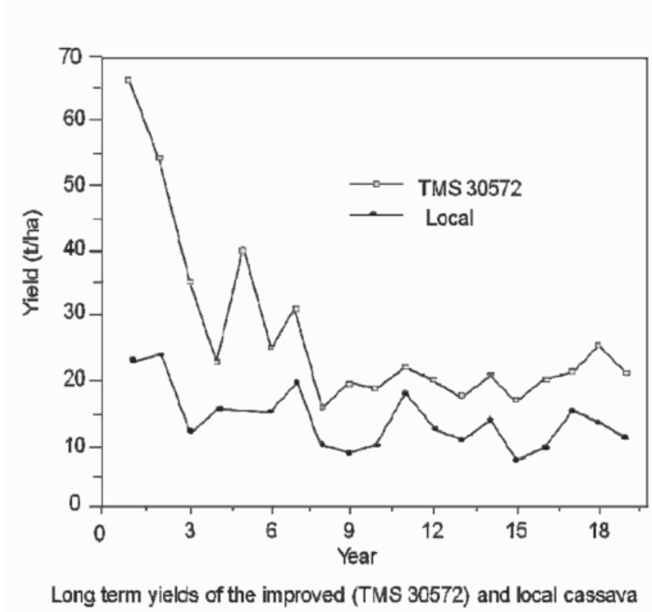


Figure 9.5. Long term yield performance by an improved cassava variety (TMS 30572).

Cassava may be grown alone, but intercropping is common in about 50% of its production area (Leihner 1983). Various geometric intercropping arrangements are practiced in Africa ranging from mixing cassava with other crops on the same hill or row, as practiced in western Nigeria, to planting cassava along definite rows (Lal 1987). In Ghana for instance, cassava intercropping ranges from the frequency of 43% in the forest zone to 95% in the coastal agricultural zones (Annor Frempong 1994). Cassava intercropping has several advantages over the monocrop including reduction of soil erosion as ground is more thoroughly covered during early growth stages, and yield stability achieved through minimizing adverse effect of weeds, pests and diseases. Reduction in soil erosion minimizes nutrient loss and prevents rapid soil fertility decline. Nitrogen-fixing legumes often perform well as an understorey intercrop. Cassava monoculture is wasteful of growth resources from the standpoint of initial runoff, soil loss before canopy closure, nutrient loss in the drainage and run off. Okeke (1984) for example, observed that there is five times as much P lost in cassava monoculture as was assimilated by the crop.

Cassava can be intercropped with other food crops including maize, sweet potatoes, yams, taro and plantains (Silvester 1989). Legume intercrops such as groundnut, cowpea, common bean, soybean, mungbean and pigeon pea may further contribute to household nutrition. Based on traditional farmers' yield levels, a very conservative yield estimate of smallholder cassava intercropped with common bean is 10 t ha^{-1} of fresh cassava roots with 30% starch and 600 kg ha^{-1} of beans with 28% protein. Improved technology and practices to aid cassava and associated intercrop productivity includes choice of cultivars, planting date and density, choice of intercropped grain legumes, spatial arrangement of crops, fertilizer requirements and competition for nutrients. Other aspects such as pest management and weed control strategies are also necessary but not discussed in this Chapter.

ISFM in cassava-based systems

Cassava is often described as a poor people's food and assumed to be a crop that grows well in degraded infertile soils. Indeed cassava is a nutrient scavenger that often leaves the soil with fewer resources (Howeler 2001). Because of its bulk and long duration, cassava extracts more nutrients from the soil than most other field crops, resulting in nutrient depletion and a decline in soil fertility. Table 9.4 indicates that harvested cassava roots remove about 55 kg N, 13 kg P and

112 kg K ha^{-1} (Howeler 1991). Contrary to its reputation, cassava may export less nutrients than cereals except for its greater extraction of K. Large-scale commercial producers in South America and Southeast Asia apply as much as 300 kg of fertilizer nutrients per crop but guidelines suitable to African smallholders should be formulated from a more realistic perspective (Howeler 2001). Cassava reliably performs where other food crops such as yam, sweet potato, rice, maize fail (Kasele 1982; COSCA 1998).

Table 9.4. Average yields and nutrient removal by cassava and other crops (Howeler, 1991).

crop	yield	nitrogen	phosphorus	potassium
	t ha^{-1}	--------------	kg ha^{-1}	-------------
cassava	13.5	55	13	112
maize	5.6	96	17	26
sorghum	3.1	134	29	29
common bean	0.9	37	4	22
soybean	0.9	60	15	67

Effect of fertilizer on cassava production. Cassava is well suited to a wide range of African soils including those in semi-arid zones. There is however a wide variation in the response of cassava to different soil characteristics and fertility regimes (Kasele 1980; COSCA 1998). Cassava production is often intercropped, and some farmers amend their soils with purchased fertilizers targeted to those companion crops. Many reports suggest that cassava responds well to the application of N, P and K (Kasele 1980).

Nitrogen. Cassava requirements for N are relatively low given its biomass and excess N reduces tuber yields (Kasele 1980). Nonetheless, fertilizer trials in West Africa frequently demonstrate a response to applied N. For example, significant responses to N application were observed in Nigeria, but varied with cultivar (Obigbesan and Fayemi 1976). Cassava shows less response to N application when intercropped with maize (Kang and Wilson 1980). Response to N fertilizer increases in conjunction with additions of K (Ashokan *et al.* 1988). The efficient use of fertilizer by cassava can be increased by top-dressing and split applications as these practices minimize nutrient loss in heavy rainfall and sandy soils, and better time availability to peak demand (Ofori 1973).

Phosphorus. Phosphorus is indispensable for tuber production (Malavolta *et al.* 1965) and its deficiency can greatly reduce the growth of cassava without the expression of recognizable symptoms (Kang 1983).. For example, Howeler *et al.* (1976) observed a large P response in highly weathered Ferralsols, where P application at a rate of 65 kg P ha^{-1} increased tuber yield from about 3 to 9 t ha^{-1}. Application of 44 kg P ha^{-1} increased cassava yield by 7 t ha^{-1}. Not only does P fertilizer increases cassava yield it also increases intercropping land use efficiency. Mason and Leihner (1988) reported an increase of land use efficiency from 30% when no P fertilizer was applied to between 41-50% when a cassava and cowpea intercrop received between 22-132 kg P ha^{-1}. Cassava can tolerate low soil P and remain productive without P application where intercropped cowpeas perform poorly (Mason and Leihner 1988). Cassava is highly dependent on mycorrhizal fungi for nutrient uptake. Greenhouse trials demonstrated that cassava growth is highly enhanced in the presence of mycorrhiza and that inoculation with an effective strain results in more efficient recovery of soil P (Kang 1983). Kang *et al.* (1980) also concluded that external P suppresses mycorrhizal root infection because root infection was highest at low P concentration.

Potassium. The most important element to cassava production is potassium. Cassava requirements for K are high and large quantities are extracted from soil (Table 9.4). Potassium affects dry matter production by increasing net photosynthetic activity and accelerates translocation of photosynthates into the tuberous root (Kasele 1980). Field response to K application appears to be frequent particularly on soils with low pH and CEC (Kang 1983). Potassium responses are frequent in strongly acid Acrisols from eastern Nigeria. Kang and Okeke (1983) observed a significant response to K on a Luvisol derived from sandy parent material by cassava cropping in only the second year following land clearing. This was attributed to the characteristically low K reserves in soils derived from sandstone. Nair and Aiyer (1985) reported that as the K level increased, cassava plant height increased correspondingly, the maximum being at 150 kg K ha^{-1} and maximum tuber yield resulted from 200 kg K ha^{-1}. Clearly, cassava responds to fertilization with mineral K.

Response to other nutrients and liming. There is limited information available on the responses of cassava to secondary and micronutrients. Responses to sulphur may be expected in tropical Africa because of their low levels of many tropical soils. For example, Mg deficiency and significant responses to its application were observed on strongly acid soils in eastern Nigeria (Kang 1983).

Nutrient cycling in cassava cropping systems. Continuous cultivation of cassava leads to a decline in yield because of nutrient depletion. Reductions in the tuber yield from 30 t ha^{-1} to 10 t ha^{-1} after 10-20 years of cultivation are reported from several areas in West Africa (Ofori 1973). In Nigeria, fertilizers are recommended but this advice is seldom followed. Cassava farmers in humid West Africa rather rely upon rotation with groundnut, cowpea or pigeon pea. Cassava producers in Benin rely upon complex mucuna intercropping or rotations as a strategy for regenerating soil fertility in cassava croplands. Farmers relying upon legume intensification adapt their cropping sequences to meet their immediate food security and cash needs while maintaining the fertility of their soils.

Long-term observation of monocropped cassava grown on a Luvisol at IITA has demonstrated that cassava yields were sustained for a period of more than a decade without external inputs. This trend is probably due to local inherent soil fertility coupled with efficient nutrient recycling of crop residues. Nweke *et al.* (2002) reported that soils of cassava fields were higher in total nitrogen, organic matter, calcium, total exchangeable bases and pH than soils of other staple crops. The use of cassava as a soil fertility regenerating crop seems to contradict the claim that cassava impoverishes soils, however, several studies (Howeler 1991, 2001, 2004) have demonstrated that cassava removes less N and P per ton of dry harvest product than most crops and a similar amount of K. The amount of nutrients removed in the tuber harvest depends upon climate, soil fertility conditions and crop variety. Stems of cassava should be returned to the field either as recycled inputs or planting materials for purposes of nutrient recycling.

In a study conducted by Adjei-Nsiah *et al.* (2006) in the forest margin in Ghana, the beneficial effect of cassava on maize grain yield was mainly due to the relatively high amount of N that was returned to the soil through litter and green leafy biomass of proceeding cassava. This is, however, recycled N, since cassava does not have the capacity to fix atmospheric N. It is also worthy to note that the cassava removed large amounts of N from the system and yet performance of maize after cassava was comparable with that of maize in land previously cropped to mucuna and pigeon pea, two symbiotic N_2-fixing legumes. This study site was quite fertile as evidenced by the high tuber yield as well as the large negative balance of 244 kg ha^{-1} N. We cannot, therefore, exclude the possibility that on poor soils, maize may perform poorly after cassava harvest, but clearly in some cases cassava cultivation, especially with intercropped legumes, may have a regenerative effect on soils.

Strategic interventions and investment in ISFM for cassava-based systems. ISFM strategies appropriate to cassava production in the humid tropics are not fully developed but investments in this area offer huge potential because significant gains in productivity are likely and cassava and its intercrops are important as both a food and cash crop. Investments in this area require that research efforts be directed first toward establishing fertilizer requirements and accompanying ISFM practices for cassava before they are formalized and disseminated as extension information. Efforts must be focused upon developing candidate ISFM practices and accompanying diagnostic tools for improved fertilizer and organic resource management. Furthermore, the investment in ISFM capacity may be combined with efforts to disseminate improved crop varieties of both mosaic resistant cassava and dual-purpose grain legumes. When field trials are directed along sound ISFM principles and conducted at a scale involving thousands of households, possibility exists to recover the costs of on-farm trials through increased food production while formulating needed nutrient management guidelines (see Chapter 14).

ISFM in rice cropping system

Rice *(Oryza spp.)* is an important staple in Africa but growing demand for this food poses an economic challenge to its nations. Annual rice production in sub-Saharan Africa is estimated to be 12 to 17 million MT (FAO 2004a) comprising 15% of the region's cereal production. Most of this rice is produced and consumed by small-scale farmers, however, preference for rice within Africa is growing by 6% per annum (WARDA 2005) resulting in a current deficit of 6.5 million MT per year valued at US $1.7 billion (FAO 2004a). West Africa alone accounts for 8.7% of world rice imports with annual demand continuing to rise by 9.3% while sub-regional production increases by only 3.7%. This large, and largely unnecessary, outflow of foreign exchange has serious consequences in terms of national development agendas and unmet expectation in living standards among Africa's people.

Insufficient rice production also affects the wellbeing of over 20 million smallhold farmers who depend upon it as their main food (WARDA 2005). Rice is an important staple food of African rural households, containing about 82% carbohydrate and 7% protein. Household dependence upon rice is greatest in West Africa, including Nigeria, Cote d'Ivoire, Guinea, Sierra Leone and Mali, but also occurs in Central, East and Southern Africa, particularly D.R. Congo, Tanzania and Madagascar, respectively. Rice yields are low in Africa, between only 1 and 2.8 tons per hectare, depending upon the production system. These yields represent less than 30% of what could be secured if better adapted and higher yielding rice varieties were better managed (DeVries and Toenniessen 2001). Nitrogen deficiency and low nutrient use efficiency rate among the leading constrains to upland rice production while salinity is a recurrent problem in rice grown in coastal lowlands and mangrove swamps (DeVries and Toenniessen 2001). Progress is being made in developing higher yielding and more pest and disease resistant rice varieties and extending them to African farmers (Sayang *et al.* 2002) but severe agro-climatic and edaphic constraints, and the inability of small-scale farmers to access the inputs necessary to overcome them limit the gains from those efforts.

Many of the challenges relating to nutrient management in rice production are based upon the wide range of agro-ecologies where rice is cultivated. In West Africa, four million ha of rice is grown in irrigated (12%) and flooded (31%) lowlands, in mangrove swamps (4%), in and along rivers (9%) and in rainfed uplands (44%), (Defoer *et al.* 2003). Basically, rice may be grown under two contrasting water regimes, as an upland field crop or in saturated, flooded lowland soils. Soil fertility constraints and their correction through ISFM vary between these upland and lowland systems.

ISFM of upland rice. Upland rice is a field crop that requires well drained soil and assured rainfall of >750 mm, making it well suited to the humid forest zone (Purseglove 1972) although some newer fast-maturing varieties require as little as 450 mm per crop (Jacquot and Courtois 1987). It is suitable as both an intercrop and in rotation with grain legumes. Because of its susceptibility to numerous pests and diseases, upland rice is best grown in complex crop rotations, and performs better after grain legumes or cotton than following maize or sorghum

(Jacquot and Courtois 1987). In addition, upland rice performs poorly as an understorey intercrop in the humid forest zone because of excess shading, but performs well within strip cropping. Intercropping upland rice with soybean or green gram can reduce bird damage to the crop but requires hand weeding to avoid herbicide damage. Upland rice may also be grown as a ground cover in young tree plantations. Care must be taken when intercropping upland rice with aggressive crop species in drier climates because it is susceptible to drought.

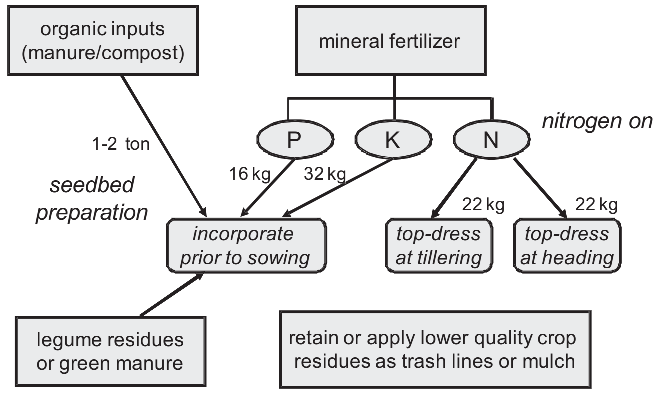


Figure 9.6. An ISFM strategy applied to upland rice (after Jacquot and Courtois 1987)

A system of ISFM for upland rice is presented in Figure 9.6. Basically, soil fertility management is conducted in three stages, with organic inputs and P and K fertilizers applied prior to planting, nitrogen fertilizer applied on demand and lower quality crop residues retained in the field as trashlines or surface mulch (Meertens 2003). Legumes such as *Mucuna* spp., *Canavalia ensiformis* and *Stylosanthes guianensis* that are established as dry season green manures provide significant amounts of nitrogen to the following crop (up to 270 kg N ha^{-1}) and significantly suppress weeds (Becker and Johnson 1998) but relay cropping with green manure legumes is often counterproductive because of unwanted crop competition (Becker and Johnson 1999a,b). Phosphorus is incorporated into the soil prior to planting because it has limited mobility within highly weathered soils and its use efficiency is improved by banding (Kirk *et al.* 1998; Bationo *et al.* 1990) assuming that seeds are planted in rows rather than broadcast. Experience in West Africa suggests there is little immediate advantage to applying phosphorus at rates of >60 kg ha^{-1} (Sahrawat *et al.* 1995) but strategies involving phosphorus replenishment remain relevant in highly weathered and nutrient depleted soils (Buresh *et al.* 1997). Top-dressed, split application of nitrogen fertilizers is practiced because mineral nitrogen is quickly lost to leaching and runoff in high rainfall areas and the rice crop has relatively low nitrogen demand prior to tillering. Low cost nitrogen fertilizers are acceptable as top-dressing because rice is able to assimilate ammonium (NH_4), and may be applied immediately before weeding so as to partially incorporate them. Upland rice is subject to lodging under excessive levels of soil N.

In the past, African farmers largely relied upon unimproved upland rice varieties but more recently a new set of varieties developed by the Africa Rice Center, New Rice for Africa (NERICA), combines the best of the properties of Asian and African rice (Jones *et al.* 1997). Advantages include higher yields (by 50% without fertilizer to >200% with fertilizer), earlier maturity (by 30-50 days), resistance to local stresses, and a 2% higher protein content. As stated previously, a feature of ISFM is the use of improved crop varieties that better respond to increased nutrient supply, and we recommend that rice producers seek NERICA or other improved varieties in conjunction with their efforts to better manage soil fertility in upland rice production systems.

ISFM of lowland rice. Lowland rice refers to that grown in saturated and flooded soils and is cultivated in and around wetlands, in coastal mangrove swamps, within the bottoms of inland valleys, on seasonally flooded river plains and under continuous irrigation. Soil properties and opportunities for management vary greatly between these systems to the extent that it is foolish to recommend a suite if ISFM practices that is universally applicable. All of these systems are, however, characterized by anaerobic soil conditions with several common features. Submerged

Table 9.5. Characteristics of three major irrigated rice ecologies in West Africa (after Defoer *et al.* 2003).

rice ecology	rice yield current	potential	Indigenous nutrient supply	Nutrient constraints	Water control	Other conditions
	------ t ha^{-1} ------					
rainfed humid lowland	2	4.5	low in inland valleys	N P K deficiencies Fe toxicity	unreliable	reduced radiation, poor input and market infrastructure, weak farmer organizations
irrigated Sahelian floodplain	4.5	7.5	high/ seasonal	N deficiency Salinity	seasonal	extreme temperatures, strong access to services and credit, strong farmer organizations
irrigated humid lowland	3	6.5	moderate/ variable	N, P, S Zn deficiencies, Fe & Mn toxicity	reliable	reduced radiation, fair access to inputs and markets, weak farmer organizations

soils have a thin oxidized layer below which is a reduced zone where nitrates may be lost as dinitrogen and N_2O. Ammonium-bearing fertilizers are readily assimilated by rice and less subject to loss than nitrates (Purseglove 1972). Micronutrients may also be reduced to forms unavailable or toxic to plants and as soils are flooded their pH increases by about 1 or 2 units. Indigenous supplies of nutrients in irrigation water and sediments provide an important but highly variable source of inputs to flooded rice systems (Haefele *et al.* 2003b) that require site specific adjustment of targeted nutrient additions as organic (Cassman *et al.* 1996) and mineral inputs (Dobermann *et al.* 2003; Witt and Dobermann 2002). Finally, these anaerobic systems emit methane into the atmosphere and are a major contributor to global climate change (Neue *et al.* 1990).

Three lowland rice ecologies, rainfed inland valleys, seasonally flooded river plain and humid irrigated systems account for more than 2 million ha in West Africa, or 73% of the sub-region's total lowland rice. A summary of the characteristics of these three rice ecologies appears in Table 9.5. Rainfed inland valleys occur in the upper reaches of river systems and cover approximately 8.5 million ha in tropical sub-Saharan Africa (Norman and Etoo 2003). Many of these valley bottoms are flooded part of the year, or contain permanent wetlands that are readily converted to rice production through the construction of small dams and local canals. The indigenous supply of nutrients tends to be low within the upper valley bottoms because alluvial processes are reduced, leading to nutrient depletion over time.

River floodplains cover about 30 million ha throughout tropical sub-Saharan Africa and about 200,000 ha of land in the Sahel along the Niger River have been placed into irrigated rice production (calculated from Defoer *et al.* 2003). River flood plains may be converted to paddy production through the construction of bunds and water distribution systems, but the cost of this conversion is relatively high, about US $10,000 per ha. Most of these seasonal paddies provide only one crop per year but offer opportunity for field cropping on residual water following rice harvest, or to double crop rice using shorter duration cultivars. On a concerned note, many of these irrigated fields are threatened by salinization from the mineral ions carried in irrigation water. About 2.5 t salt per ha of salt may be deposited during a single growing season from irrigating with water containing only 0.05% dissolved salts, a concentration common in most waters in semi-arid areas (Russell 1973). Accumulated salts are controlled by flushing them into deeper soil horizons with large amounts of cleaner irrigation water but, if that water is unavailable or once exchangeable sodium has saturated the soil minerals, land managers have few available options for land reclamation.

Irrigated rice in the humid forest zone provides the best conditions for cropping because of the continuous availability of water and warm temperatures permit year-round paddy operations. These systems do suffer from deficiencies in nitrogen, phosphorus, sulfur and zinc, and toxicities by reduced forms of iron and manganese. As a result of continuous cropping, accumulation of pests and disease is common. Pests include rodents, crabs, birds and numerous insects, particularly the gall midge and white stem borer. Diseases such as bacterial leaf blight, blast and rice yellow virus also pose a serious problem to farmers. In addition, the accumulation of aquatic grasses, particularly *Echinochloa colona*, and sedges (*Cyperus iria* and *C. difformis*) are difficult to control during cropping cycles as entry into the paddies may be restricted (Haefele *et al.* 2000). Nonetheless, there is vast potential to increase irrigation by readily converting wetlands within the humid forest zone into controlled irrigation schemes covering an additional 340,000 ha. When developing irrigation schemes and paddy lands, care must be taken to control emerging health hazards common to wetlands, particularly vectors of malaria and shistomiasis parasites (Norman and Etoo 2003).

Fertilizer management of irrigated rice is guided by an array of computer simulation models that may be employed to adjust recommendations to site-specific conditions. These models take into account target yields, nutrient use efficiency, indigenous nutrient supply, nutrient losses, harvest index and other cultural and physiological factors (see Haefele *et al.* 2003 a,b; Witt and Dobermann 2002). While these models may be intriguing to scientists, applied by regional development planners and enjoyed by computer gamers, they may prove somewhat difficult to initialize and validate within most small-scale settings. Another, more practical approach to fertilizer addition includes the use of leaf color charts although diagnostic feedback offered often occurs too late in the cropping cycle to take corrective action (Singh *et al.* 2004). Clearly, site-specific nutrient management approaches are important, but they must also be realizable within the context of the resources and skills available to African small-scale farmers. A straightforward approach to recommending the addition of mineral fertilizers is to identify general inherent fertility levels and yield targets and to adjust them to additions from organic and biological sources (Witt and Dobermann 2002).

Fertilizer recommendations for irrigated rice appear in Table 9.6 and in Donovan *et al.* (1999) and Wopereis *et al.* (1999). These rates assume that non-saturated soil is being worked prior to the cropping cycle and should be increased slightly for continuously flooded conditions (Dobermann and Fairhurst 2000). All P is applied at the onset of the season, but potassium applications may be evenly split as pre-plant incorporation and top-dressed at panicle initiation (Witt and Dobermann 2002). Note that in more fertile conditions, no mineral nitrogen is recommended to achieve yield levels of 4 t ha^{-1} because the indigenous supply of nutrients arriving in water and sediments and that mineralized from unamended saturated soils is sufficient for crop demand. For example, indigenous nitrogen measured in four West African countries ranged between 26 and 62 kg N per ha per crop (Haefele *et al.* 2003b) but this supply must not be taken for granted as it is tremendously variable (Dobermann *et al.* 2003a,b) and considerably reduced within the upper reaches of inland valleys.

Nitrogen is difficult to apply and retain within flooded and flowing lowlands but several approaches may be combined to assure efficient and reliable N supply. The general principles of integrated nitrogen management within irrigated rice include; 1) accounting for indigenous nitrogen supply (Cassman *et al.* 1996), 2) promoting BNF by blue-green algae (Reddy and Roger 1988) and symbiotic azolla water ferns (Watanabe 1982) within the paddies during flooding, 3) growing grain legumes or short term improved fallows prior to rice cropping (Giller and Wilson 1991, Gypamantasiri *et al.* 2004) , 4) applying pre-plant N at sites where indigenous

Table 9.6. Fertilizer recommendations adjusted for indigenous supply of nutrients and target rice yields (after Dobermann and Fairhurst 2000).

Indigenous supply of nutrients	target rice yield t ha^{-1}	Recommended addition N	P	K
		--------	kg ha^{-1}	---------
Low	4	70	10	30
	7	175	42	125
Moderate	4	0	10	15
	7	135	23	70
High	4	0	10	25
	7	90	18	45

N supply and inputs from BNF are low and 5) applying remaining N fertilizer in two splits at critical growth stages (e.g. tillering and heading), with an additional late season application of N to improve grain filling if the crop stand is in good condition (Witt and Dobermann 2002).

While it is not feasible to intercrop nitrogen fixing legumes and lowland rice, these two crops can be grown in rotation. Chickpea (*Cicer arietinum*), green gram (*Vigna radiata*) and soybean (*Glycine max*) are well suited as second crops following rice, able to withstand early waterlogging and efficiently use residual water as the rice paddy dries (Duke 1981; Malik *et al.* 2002; Singh *et al.* 1999). These three legumes are capable of 84, 107 and 188 kg of BNF per ha, respectively, over a few months (Giller and Wilson 1991). To gain an early start, these legumes may be planted into saturated paddy soils by placing seeds into open planting holes up to 14 cm deep (Garrity and Liboon 1995). Alternatively, *Sesbania rostrata* may be grown as a green manure following paddy rice to accumulate as much as 123 kg N per ha within only 55 days (Gypamantasiri *et al.* 2004). *S. rostrata* is particularly effective as a nitrogen fixing green manure in saturated paddies because it forms symbiotic stem nodules with rhizobia, rather than root nodules, that have better access to atmospheric gasses (Giller and Wilson 1991). Establishing trees on the bunds separating rice paddies can impact negatively upon rice yields as the shading effect may more than offset benefits derived from the trees' organic input addition (Sae-Lee *et al.* 1992).

Within the fuller context of rural development, rice cultivation is also an important mechanism for livelihood diversification by small-scale farmers. Many cash crops and vegetables may be grown as intercrops of upland rice or in rotation with paddy rice (Purseglove 1972, Jacquot and Courtois 1987, Olaniyan *et al.* 2002). Water management of irrigated rice lends itself to aquaculture as a means of improving diets, generating income and better recycling nutrients and water (Haefele *et al.* 2003). Rice bran and straw are important animal feeds. In this way, integrating rice, vegetables, fish and livestock enterprises is an important, but still under-utilized, means of empowering household to move from subsistence farming to mixed-enterprise agriculture.

ISFM in banana-based cropping systems

Banana and plantain are extremely important crops throughout the humid forest zone and in the Lake Victoria Crescent, where they serve as both staple food and a source of income (Stover and Simmonds 1987). The pseudostem and leaves of banana can also be used for mulch, livestock feed, handicrafts, and in paper production. Banana stands protect agricultural resources because of the plant's perennial growth and nearly closed canopy that serves to reduce erosion and promote soil health. Young stands of bananas are often intercropped, allowing for diversified farm enterprise and the interchange of crop residues (Bekunda and Woomer 1996). Despite these advantages, however, bananas are suffering from yield decline because of the accumulation of new pests and disease and continuous nutrient depletion resulting in reduced productive lifespan (Bananuka and Rubaihayo 1994; Bwamiki *et al.* 1998).

A simple strategy for ISFM in banana-based cropping has resulted from practical experience in East Africa. Select banana fields carefully as the crop performs poorly under waterlogged and drought conditions (Stover and Simmonds 1987; Sama-Lang 2004). When first establishing banana, plant disease-free offshoot swords or tissue cultured seedlings into prepared holes that contain about 100 g N-P-K fertilizer and 500 g of compost or animal manure, and apply mulch around the base of the plant. Cut grass such as napier (*Pennisetem purpureum*) is particularly well suited as a nurse mulch because of its high nutrient content (2.0% N, 0.14% P and 3.9% K). Banana is cultivated between 9 m^2 (3 m x 3 m) and 25 m^2 (5 m x 5 m) per mat, leaving sufficient open area for intercropping. Till this open area, apply 30 kg P per ha as mineral fertilizer and plant nitrogen-fixing grain legume intercrops such as groundnut, cowpea or soybean (Eaglesham *et al.* 1982). Retain the legume residues as surface mulch, and periodically apply manure, compost, field crop residues or cut grass to the bananas as mulch. After 14 to 18 months, apply

25 kg K ha^{-1} as the first bunches emerge. Harvest bananas, and use pseudostems as livestock feed and handicrafts as needed, retaining the remaining residues in the field. Feed all peels to livestock and collect the manure. As the banana canopy closes, grow intercrops that require less radiation such as beans or vanilla. Cassava and sweet potato intercrops suppress nematodes affecting banana (Talwana *et al.* 1997). Alternatively, a shade tolerant ground cover legume may be established as a continuous source of fixed nitrogen. Each year, reapply 50 grams of N-P-K fertilizer per banana mat in conjunction with the addition of manure, compost or surface mulch. For heavy clay soils, best results are achieved when applied organic inputs are partly worked into the soil (Zake *et al.* 2000).

Small-scale farmers have numerous options for organic resource transfers within banana fields and between other farm enterprises (Figure 9.7). The most common field practice is to retain banana pseudostems and leaves as mulch, a practice that likely contributes to the accumulation of banana's many pests and diseases. Despite this threat, mulching with banana residues result in substantial yield improvement, presumably due to nutrient recycling (Mcintyre *et al.* 2000). Alternatively, these residues may be transferred to other crops, fed to livestock or composted, but these options are seldom applied. For example, applying 5 tons of banana pseudostems per ha to cabbage as a surface mulch increased cabbage yields by 12.5 t ha^{-1}, an effect that was more related to nutrient supply than weed suppression (Lekasi *et al.* 2001). Mulching with banana also stimulates the population of earthworms and other soil macrofauna, and maintains higher rates of soil nitrogen mineralization. Despite these advantages, field crop residues, livestock manures and composts are more often applied to bananas, suggesting that this crop is viewed as a priority among farmers (Bekunda and Woomer 1996). Far too few farmers apply mineral fertilizer to banana. Recommendations for this crop are extremely high compared to their availability and price, 100 kg of N and K per ha per year (Nkedi-Kizza *et al.* 2002), suggesting that whatever mineral fertilizers are applied should be strategically combined with organic resources.

Banana decline is now considered a reversible phenomenon, but one that requires inputs that are too often beyond the reach of poor farmers who are most affected. A Diagnosis and Recommendation Integrated System (DRIS) that monitors N, K and Mg as the most limiting nutrients to banana is available (Smithson *et al.* 2001) but practical only for large commercial operations. Severely degraded banana mats may be cut near ground level and the residues applied as mulch to a cereal-legume intercrop (Woomer *et al.* 1998a). As new banana shoots emerge from

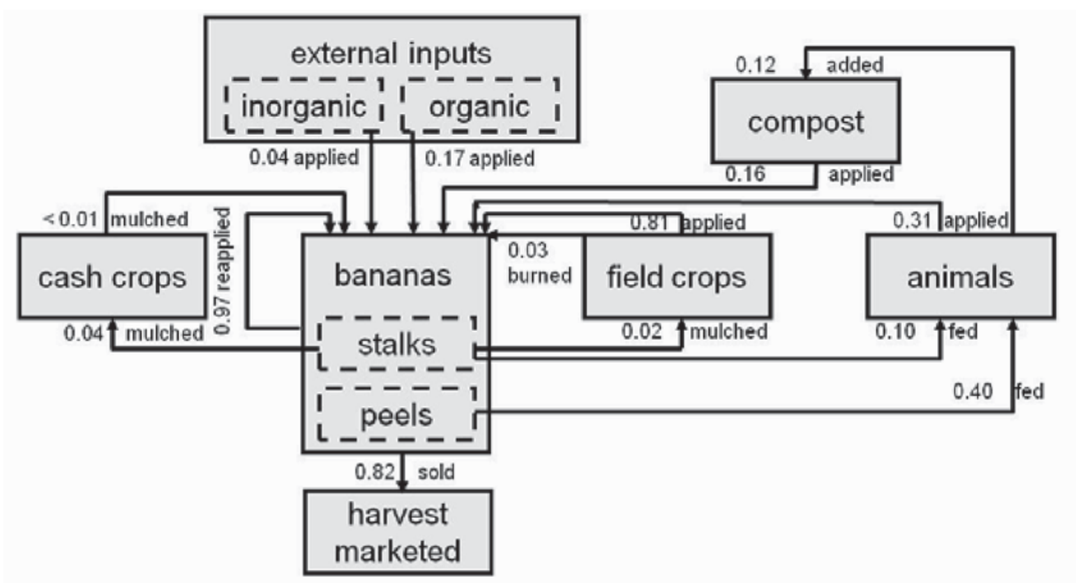


Figure 9.7. Frequency of input application and transfer in banana-based cropping systems of Uganda (after Bekunda and Woomer 1996).

the mats, they are heavily mulched with field crop residues and intercropped with nitrogen-fixing legumes. As the first bunches appear, mats are top-dressed with N and K fertilizer. Within all banana operations, continuous IPM is essential, including use of disease-free planting material, trapping of banana weevils with lures and spraying outbreaks of pathogenic foliar fungi (Gold *et al.* 1999).

Accelerating change in humid farming systems

Soil resource degradation is occurring throughout the humid forest zone, regardless of population density, but is most pronounced where bush fallows have reached critically low thresholds. The process of land transformation therefore hampers food security, limits efforts to alleviate poverty, and constrains human development in areas near towns and market centers. Access to older tree fallow across Africa's humid forest zone is becoming limited, forcing land managers to make more extended use of cultivated land and more effective use of shorter fallow intervals. Specific land management options largely depend upon the local agro-ecological and socio-economic conditions. In higher population areas, agricultural change is driven by the need for increased food production on smaller pieces of land. This situation exists in DR Congo, Cameroon, the Republic of Congo and the Central Africa Republic where farmers are facing shorter fallow periods, degrading soil fertility, spread of noxious and parasitic weeds, and poor accessibility and affordability of needed external inputs such as fertilizers and herbicides. Adoption of improved fallows and complex agroforestry systems is imperative in such degrading lands.

As traditional bush fallows tend to become shorter or eliminated entirely, the challenge is to manage agricultural lands in a manner that stabilizes or better, improves crop productivity. Simply stated, slash-and-burn agriculture or even short-term natural fallows are no longer feasible in many parts of the humid forest zone and ISFM strategies must be devised that complement continuous, productive cultivation of soils with inherent low fertility and, in many cases, unfavorable soil surface properties. In areas with better access to farm inputs and developed commodity markets, such as Nigeria, Cote d'Ivoire and Ghana, farmers have already abandoned the fallow system and are now confronted with severe physical degradation of soil and nutrient depletion because their transition to market agriculture has not kept pace with their deteriorating resource base. ISFM practices are available to assist these farmers within intensified mixed cropping systems, especially as opportunities for marketing production gains in cassava, rice, bananas and grain legumes unfold, creating demand for accompanying farm inputs.

Guidelines for future research and development activities include maintenance of soil organic matter, critical nutrient levels and soil surface cover, reduction of soil erosion and intensification of farming systems that incorporate mixed cropping agroforestry, nutrient recycling, mulching, and reduced tillage. In time, diagnostic soil testing as described in Chapters 11 and 12 is vital. More research is needed in the areas of intercropping cassava with other crops especially multipurpose grain legumes as a means of increasing nitrogen inputs into these cropping systems.

Chapter 10. Conservation Agriculture

Conservation Agriculture is a recent and evolving concept to land management that seeks to optimize crop yields and farm profits in a manner that balances economic and environmental benefits (Dumanski *et al.* 2006). It emerged as a refinement of no-till farming within large-scale mechanized field cropping in North and South America and is being modified to suit other farming systems and locations (Goddard *et al.* 2008). Advocates of Conservation Agriculture maintain that intensive soil tillage is unnecessary and ill-planned because it leads to soil degradation and loss of crop productivity. Alternatively, Conservation Agriculture is built around a suite of land management principles that integrate ecological management with scientific agriculture through minimal disturbance of the soil. These principles may be summarized as; 1) avoiding soil tillage, 2) maintaining soil cover and retaining crop residues, 3) practicing crop rotations and improved fallows, and 4) promoting the use efficiency and precision placement of applied fertilizers, pesticides and herbicides.

Table 10.1. Total coverage of Conservation Agriculture (ha) compiled between 2003 and 2007 (FAO 2008)

Country	coverage (ha)
Brazil	25,501,000
USA	25,252,000
Argentina	19,719,000
Canada	13,480,000
Australia	9,000,000
Paraguay	2,094,000
Kazakhstan	1,790,000
Uruguay	1,082,000
Bolivia	550,000
South Africa	377,000
Spain	300,000
Venezuela	300,000
France	150,000
Chile	120,000
Colombia	102,000
China	100,000
Mexico	22,000
Total	99,862,000

Conservation Agriculture is practiced on approximately 99 million ha with most of this production in Brazil (26%), USA (25%), Argentina (20%) and Canada (13%) and significant coverage also occurring in Australia and Paraguay (Table 10.1). Increases in coverage by Conservation Agriculture over the past fifteen years are about nine-fold (Figure 10.1) and farmers practicing Conservation Agriculture are expected to increase substantially in the near future, particularly in South America. On the other hand, difficulties exist in translating the principles of Conservation Agricultures into field practices attractive to small-scale farmers elsewhere in the tropics. This situation is particularly relevant in sub-Saharan Africa where smallholders lack access to necessary knowledge, equipment and inputs that reduce farmers' reliance upon hand tillage and animal traction for seedbed preparation and weed control (Binsinger and Siller 1983). Household dependence upon crop residues for other purposes such as livestock feed, fuel and shelter further complicate adoption.

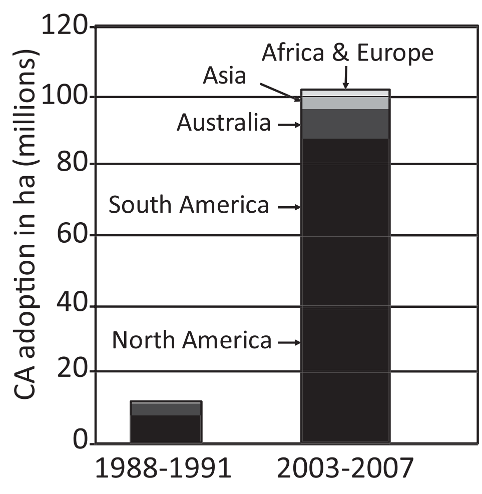


Figure 10.1. Increase in the coverage of Conservation Agriculture in different areas of the world (after FAO 2008).

The Plowman's Mindset

To a large extent, the plow is nearly synonymous with agriculture. Hand hoes and livestock drawn plows were among the earliest agricultural inventions. The development of a mouldboard plow by Jethro Tull was considered a revolutionary labor saving development. Indeed, subsequent mechanical tillage was viewed as an expedient means of simultaneously preparing a seed bed, burying weeds and accelerating nutrient mineralization. In addition, the earliest stages of agricultural mechanization were based upon the need for clean, tilled fields and subsequently developed machinery generally followed suit (Friedrich 2000). In this manner, conventional agriculture became the foundation of agricultural science and was only challenged through the advent of sustainability as a land management and development objective. At this point, many agriculturalists broke with tradition and concluded that long-term intensive soil tillage leads to the deterioration of soil physical and biological properties and the loss of land productivity (Derpsch 2008).

Proponents of Conservation Agriculture argue that soil tillage is unnecessary and destructive. They point out that the earliest planting was performed with a stick in unprepared soil and that practice proved effective for many centuries. They advocate that soil biota and roots naturally turn the soil and that organic recycling serves as a constant supply of mineral nutrients. Faulkner (1943) challenged the need for tillage in his book *"The Plowman's Folly"* by stating that "*no one has ever advanced a scientific reason for plowing"* and *"the plow has actually destroyed the productiveness of our soils*". Despite these conclusions, no-till agriculture could not be practiced without the advent of herbicides and their delivery systems to control weeds. During the 1950's and 1960's, agricultural chemical companies pioneered no-till technologies in the USA and Europe that were adopted and modified in South America during the 1970's. Thus no-till farming became an option for large-scale mechanized agriculture through the refinement of crop varieties, seed planters, spraying equipment, herbicides and harvesters specially suited to Conservation Agriculture. Most recently, soil carbon sequestration was identified as an additional benefit of Conservation Agriculture (Lal 1997; Reicosky 2008) although debate surrounds the recognition, measurement and repayment for this important below-ground carbon sink (Noble and Scholes 2001).

Although advocates of Conservation Agriculture argue that its benefits are substantiated, technologies available and conversion from conventional practice understood, but why then have a vast majority of farmers been unwilling to adopt these practices? Many proponents point to farmers' conservative mind set and an unwillingness to undertake so radical a departure in field operations (Derpsch 2008). Farmers committed to regular tillage find it counterintuitive that conservation practice results in reduced soil compaction and less water infiltration. In many cases, their agriculturalist and extension peers reinforce this misperception. Others suggest that the long transition period before full benefits of Conservation Agriculture, up to 20 years, is beyond the planning horizon of many farmers (FAO 2008). Others indicate that conservation practices remain specific to certain crops and within defined cropping systems and are not readily adapted, particularly by smaller, mixed enterprise farmers (Derpsch 2008). Whichever the case, an examination of Conservation Agriculture in terms of its underlying principles, field practice and input management strategies is of particular interest in the development and refinement of ISFM in Africa.

Principles and Practices

No tillage. Minimal physical disturbance of soil through zero tillage is a fundamental principle of Conservation Agriculture. Avoiding tillage is intended to avert disruption of soil aggregates, protect soil organic matter from accelerated decomposition (Table 10.2) and restore several soil biological processes. For example, permitting dead roots to decompose intact and fostering soil macrofauna, especially earthworms, serve to

Table 10.2. Carbon and nutrient contents of soils under no-till (NT) and conventionally tillage (T) in the US Midwest.

Soil depth	Carbon		Nitrogen		Phosphorous	
cm	(%)		(%)		(mg kg^{-1})	
	NT	T	NT	T	NT	T
0-5	2.5	1	0.3	0.1	100	20
15-Oct	1.3	1	0.2	0.1	10	40

After CTIC Partners 2000.

naturally restructure soils through inter-connective channeling, improving macro-aggregation, water infiltration and easing root penetration for the following crop.

Because tillage is avoided, other means must be found to control weeds. Weeds are managed through the use of pre-emergent and post-emergent herbicides, dragging chains and pulling knives mounted on rotating drums. Generally, these measures require tractors but in many cases these devices are being modified for animal traction. Reduced tillage is an energy saving innovation (Figure 10.2), with only a small fraction of fuel consumption required for a tractor to pass through a field without plowing (Nalewaja 2001).

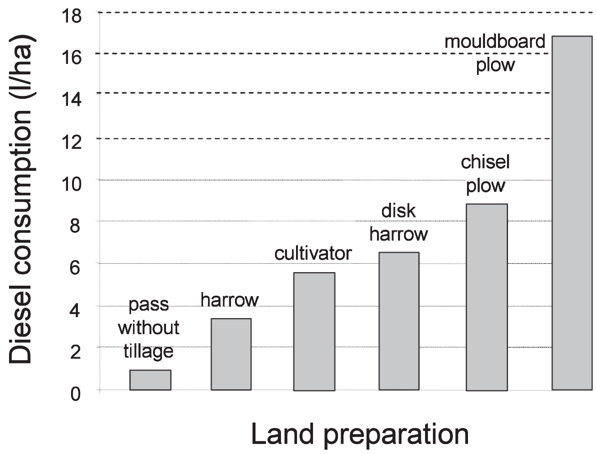


Figure 10.2. Diesel fuel consumption while performing different tractor operations (after Nalewaja 2001).

Maintain permanent soil cover. Conservation practices advise against the removal of crop residues, suggesting that stubble be left intact and dried stems and leaves, referred to as stover or trash, are chopped and used as mulch to cover the soil surface. Maintaining permanent soil cover protects against erosion (Figure 10.3), suppresses weeds, increases water infiltration and promotes soil biological activity. Note that a large degree of soil protection is achieved from the first 30% of soil cover and soil loss reduction is attenuated beyond 80% mulch coverage. Seeds are planted by shallow drilling through the crop residue mulch, or in manual systems jabbed into the soil and the emerging seedlings are protected by the surrounding crop residue mulches. Soil cover is provided by retaining crop residues as surface mulch and by establishing cover crop rotations and relays. Over several years, a soil under Conservation Agriculture develops an organic surface horizon that promotes a healthy, living soil and serves to recycle organic matter in a manner similar to natural ecosystem. Within the context of Conservation Agriculture, crop residues are regarded as important organic resources and burning them is anathema.

Diversify crop sequencing. Crop rotation is another fundamental principle underlying Conservation Agriculture. This crop sequencing take the form of simple and complex rotations, relay cropping, strip cropping and periodic green manure cover crops. Symbiotic legumes play an extremely important role in crop sequences because of their potential nitrogen contribution to the soil (Giller and Wilson 1991). Under mechanized Conservation Agriculture, it is difficult to intercrop cereals and legumes because of the importance of herbicides for weed control, but in less intensive, manually weeded systems, legume intercrops occupy another important role as understorey cover that provide pulses, increase symbiotic N-fixation and assist in the maintenance or

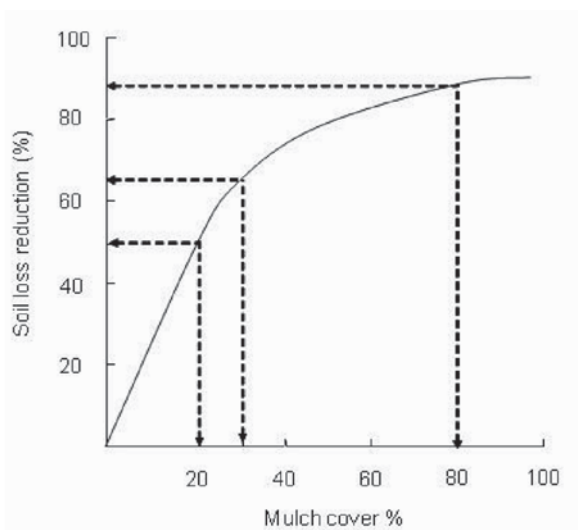


Figure 10.3. The relationship between mulch cover and loss to soil erosion.

Table 10.3. Field legumes with important roles in crop sequencing within Conservation Agriculture

Legume	Role (s)	Drought resistance	Weed suppression	Shade tolerance	Potential BNF	Food/feed value	Comments
Soybean *Glycine max*	rotation	moderate	moderate	low	high	high/high	Rhizobia specific & promiscuous types
Lablab *L. purpureus*	rotation/ relay	high	high	moderate	high	high/high	Use trailing, rust resistant types
Groundnut *Arachis hypogaea*	rotation/ intercrop	high	low	moderate	moderate	high/high	Bunch & runner types, use rosette resistant types
Common bean *Phaseolus vulgaris*	rotation/ intercrop	low	low	high	low	high/ moderate	Bush & climbing types, many pests
Cowpea *Vigna unguiculata*	rotation/ intercrop	low to moderate	low	moderate	moderate	high/ moderate	Bush, trailing & climbing types
Golden gram *Vigna radiata*	rotation/ intercrop	moderate	moderate	moderate	moderate	high/high	Use rust resistant types
Pigeon pea *Cajanus cajan*	rotation/ relay	high	low	low	high	high/high	Shrub & dwarf types
Mucuna *Mucuna spp.*	cover crop	moderate	high	low	high	none	Extremely vigorous & competitive
Jack bean *Canavalia ensifornis*	cover crop	high	moderate	high	high	none/ low	Seeds with industrial uses
Tephrosia *Tephrosia spp.*	improved fallow	high	low	low	high	none	Produces rotenone insecticide
Sesbania *S. sesban, others*	improved fallow	low	low	low	high	none/high	Agroforestry applications

permanent soil cover. Several of these legumes and their roles within Conservation Agriculture in the tropics appear in Table 10.3.

Better target inputs. Conservation Agriculture includes the precision placement and timing of inputs in order to reduce production costs, optimize their use efficiency and minimize environmental damage. Precision is exercised within many areas including seed placement, fertilizer application and during pesticide spraying operations (Dumanski *et al.* 2006). Precision includes avoidance of blanket field operations, but rather different positions of the field and farm are managed based upon growing farmer experience. Herbicide applications are adjusted for weed composition and whenever possible spot treated. Because contour furrows are not created, row orientation may better optimize available radiation, particularly improving light penetration to understorey crops. Fertilizers are necessarily top-dressed into the soil cover rather than incorporated and this may affect the form, timing and rate of mineral nutrient application. In some cases, amendments that perform best when reacted with the soil, such as lime and rock phosphates, perform at lower efficiency during the earlier adoption of Conservation Agriculture but other fertilizers, particularly nitrogen top-dressing, are more efficiently used by crops because of greater nutrient retention and beneficial organic x inorganic interactions.

Rely upon Integrated Pest Management. Conservation Agriculture operates within the full context of Integrated Pest Management by first controlling pest and disease through crop variety selection and sequencing, and then through judicious application of pesticides. Another advantage is the improvement of soil biological diversity and its development of complex food webs that operate against parasitic and destructive organisms. Full advantage is also sought from pest control by released and fostered predators, and the use of biological agents and bio-

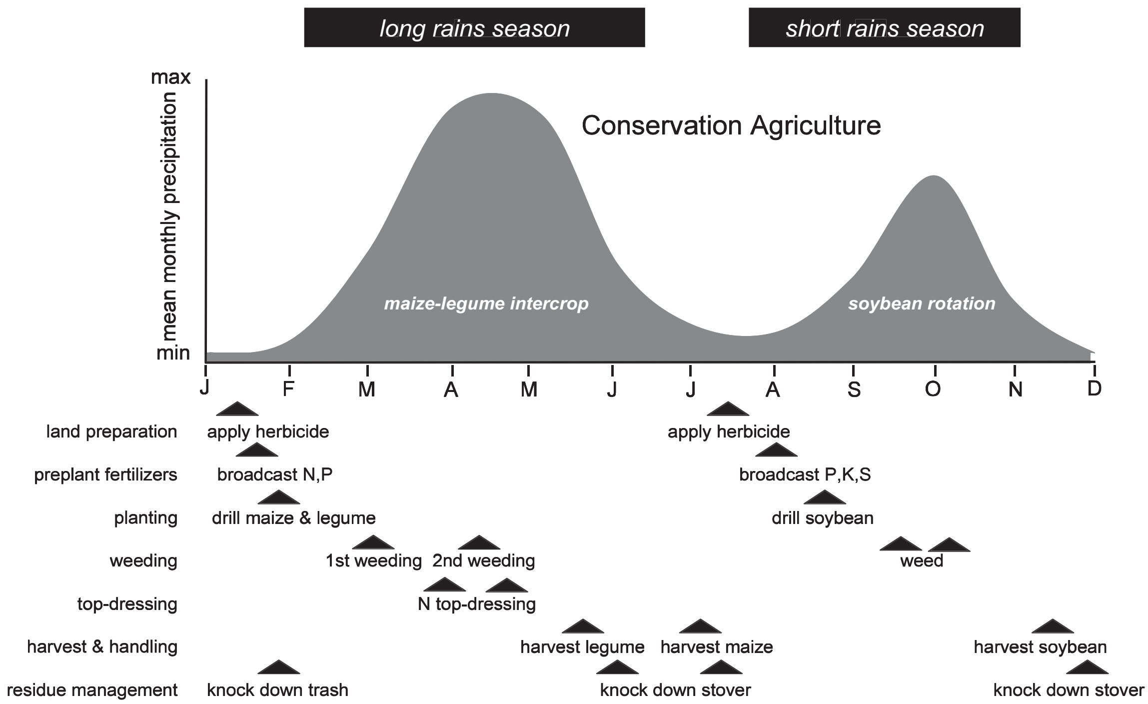


Figure 10.4. ISFM practice within the context of Conservation Agriculture in a sub-humid bimodal rainfall regime.

pesticides. In this way, biological control of pests forms a safety net protecting crops as pest and disease outbreaks become less severe and frequent (Derpsch 2008).

Avoid soil compaction. Avoidance of soil compaction is a more recently developed principle of Conservation Agriculture and one that is based upon experience of fully mechanized systems. Soil compaction under Conservation Agriculture occurs as a result of repeated passes of tractors and field implements and is not confined to deeper soil zones, as develops beneath the plow layer with conventional tillage. Frequent passes of heavier equipment contribute to this compaction that is greatest when soils are worked in a wet condition or over time in sands with little capacity to self-ameliorate (Rainbow 2008). Because much of the soil compaction occurs during the first few passes, it is advantageous to establish permanent wheel lines through the field. Balloon-type tires limit soil compaction as well but are not yet widely available.

Soil compaction may also develop near the soil surface as a result of seed drills and this liability is not readily addressed through establishing wheel lines. The greatest protection from soil compaction rests in permanent litter layers which serve to cushion the soil from pressure above. In fairness, Conservation Agriculture was not intended to alleviate soil compaction and reduction of soil density occurs slowly as soil organic matter and porosity increases. More severe incidence of soil compaction are best addressed prior to conversion to Conservation Agriculture and it may prove necessary to correct soil compaction that develops over several years using conventional chiseling and ripping (Benites 2008).

Conservation Agriculture in practice

Proponents stress that Conservation Agriculture may be viewed as a basket of options available to farmers with practitioners free to chose which practices best suit their conditions and goals. Some field practices, such as soil tillage, burning crop residues or natural fallows, run counter to the principles of Conservation Agriculture for obvious reasons. Conservation Agriculture does not prohibit the use of particular inputs, as does organic agriculture, rather it stresses that they must be applied at times and rates that cause minimal disturbance to beneficial soil organisms and processes.

An example of the field operations of a Conservation Agriculture system where maize-legume intercrops are grown in rotation with soybean in a tropical climate and bimodal rainfall is presented in Figure 10.4. Note that maize is grown in the longer, more plentiful rains and that soybean is produced during the shorter growing season. Rather than practicing tillage at the onset of the growing season, weeds are treated with herbicide, seeds are drilled and fertilizer is top-dressed. From here out, field operations resemble conventional practices until harvest where care is taken to retain stubble and to chop and mulch crop residues. Conservation Agriculture guidelines suggest that 5 to 8 tons of crop residues be applied as soil cover per year and that less disposes the soil to erosion and more may interfere with field operations (Goddard *et al.* 2008). Note that this suite of field practices may be conducted using either manual field labor or with specialized field equipment.

Transition from conventional to Conservation Agriculture. Conservation Agriculture is designed to improve soil properties over several years, improving soil physical, chemical and biological properties and allowing crop production to respond profitably to fewer, more strategically applied inputs. This process of soil improvement that results during the transition from conventional to conservation systems may be separated in specific steps termed the early, consolidation and maintenance phases of Conservation Agriculture (Sá 2004). Farmers generally accept Conservation Agriculture after they are convinced that intensive tillage has accelerated erosion, disrupted soil aggregation, reduced soil organic matter and interfered with beneficial soil biota and processes. Prior to the adoption of no-till, land managers have the option of applying and incorporating large amounts of soil amendments, such as limestone or rock phosphate, into the soil. About five years (or growing seasons) of no-till conservation practices are required before soil properties improve through continuous no-till and full stubble and residue retention (Derpsch 2008). Over the following five to fifteen years (or seasons) there is an increase in the size and stability of soil aggregates, an increase in nutrient and water holding capacity, soil organic matter and organic N and P and the formation of a litter layer on the soil surface. After about twenty years (or seasons) the soil surface has developed a surface organic (O) horizon, soil organic C has maximized, nutrient mineralization attenuates at a higher level, and fertilizer and soil water use efficiency remains markedly improved. These features are further described in Table 10.4.

Advantages of Conservation Agriculture. The adoption of Conservation Agriculture brings not only direct financial rewards to farmers but also broader community and environmental benefits (FAO 2008). Farmers receive greater yield stability, higher economic returns to inputs, reduced demand for fuel and labor, and greater retention of water and nutrients in the soil.

Communities enjoy greater hydrological benefits from more reliable and cleaner supplies of water and greater soil infiltration results in less flooding, sedimentation and resultant destruction of infrastructure. Environmental benefits are far reaching and occur at several spatial scales. Soil and agricultural biodiversity is fostered. Soils perform as carbon sinks and thus serve to ameliorate greenhouse gas emissions. In semi-arid areas, the trend toward desertification is arrested. Mechanized Conservation Agriculture requires less energy than conventional farming, in large part because of the large fuel requirements of plowing and cultivating.

Bhan and Bharti (2008) cite several advantages of Conservation Agriculture to dryland Indian farming. Soil erosion by wind and water is substantially reduced by the presence of stubble and mulched crop residues. Soil moisture is conserved through reduced runoff, better infiltration and reduced surface erosion. Increases in soil organic matter offer numerous benefits including greater moisture holding and nutrient buffering, and provide a source of mineralizable nitrogen.

Table 10.4. Soil restoration under different phases of adopting Conservation Agriculture (after Derpsch 2008 and Sá 2004)

Intensive tillage	Phase of Conservation Agriculture (years or seasons)		
Soil properties	Adoption (0 to 5 years)	Consolidation (5 to 20)	Maintenance (>20)
Physical disaggregation	Some micro-aggregate formation	Macro-aggregate formation	Diverse, stable soil aggregates
No surface cover	Seasonal stubble and residues	Year-round litter layer forms	Organic surface horizon established
Reduced SOM	SOM loss is arrested	Steady increase in SOM	Stabilized SOM and organic recycling
Reduced soil biological activity	Microbial biomass increases	Macrofaunal services restored	Soil biodiversity and biological processes restored

Direct seeding into the previous season's stubble protects young seedlings from wind and excessive temperatures (Goddard *et al.* 2008). Weed populations decline over time. Less labor is required for land preparation and other field operations. While initial equipment costs may be higher, savings is accrued over time through less strenuous use resulting in fuel savings. Overall, Conservation Agriculture is said to offer similar yields, greater profits and protection of the soil for future use.

Conservation Agriculture and ISFM

Although not yet widespread in sub-Saharan Africa and many of its technologies are not available or well-suited to small-scale farmers, incorporation of many of the principles fundamental to Conservation Agriculture can assist in ISFM. Conservation Agriculture combines minimal soil disturbance, extensive mulching and crop rotations. It conserves soil and water, eliminates tillage and reduces labor requirements. Conservation Agriculture is practiced on a large scale in South Africa (377,000 ha) and to a lesser extent in other African nations (e.g. 35,000 ha in Ghana) with the most common crops being maize, sorghum, wheat and cotton (Derpsch 2008). Conservation Agriculture provided 1.1 tons ha^{-1} additional maize among Zambian farmers and was more profitable despite higher costs of production. Approximately 60,000 farmers in Zambia are employing two or more conservation farming techniques being promoted by their producers' associations (Haggblade and Tembo 2003). On-station trials in Zimbabwe showed an increase in maize yield from 3,200 to 4,000 kg ha^{-1} with Conservation Agriculture on well-drained soils, as a result of reduced water runoff and soil erosion. In drier locations, Conservation Agriculture increased maize yields from 2,900 to 3,600 kg ha^{-1} (Elwell 1995). Initially, decreased fertilizer N use efficiency may be observed in conservation systems because fertilizers are applied to the soil surface, however, accumulation of soil organic matter with time results in greatly improved nutrient use efficiency by crops, erosion control and soil physical properties.

Indeed, Conservation Agriculture is a powerful new trend that captures basic ecological principles and cutting edge technologies. Briefly, Conservation Agriculture practices minimum or zero tillage under the assumption that soil disturbance has a net negative effect on soil health through its disruption of soil structure, disturbance of soil biota and accelerated decomposition of soil organic matter. While ISFM is largely consistent with precepts of Conservation Agriculture, several adjustments are necessary. Pre-plant fertilizers are broadcast or banded rather than incorporated. This requirement may reduce the effectiveness of mineral lime or phosphorus application, although as soil organic matter increases, soils become better buffered, phosphorus fixation is reduced and organic phosphorus increases. Organic inputs are only applied as mulch and become less subject to decomposition and mineralization. In some cases this predisposes nutrients to atmospheric loss. In contrast, dead roots and stubble remain more or less intact. Conservation Agriculture encourages that crop residues be chopped or knocked down, and left in the field as mulch. Burning is prohibited. In this way, nutrient recycling is promoted while shortcuts to accelerated nutrient availability are discouraged.

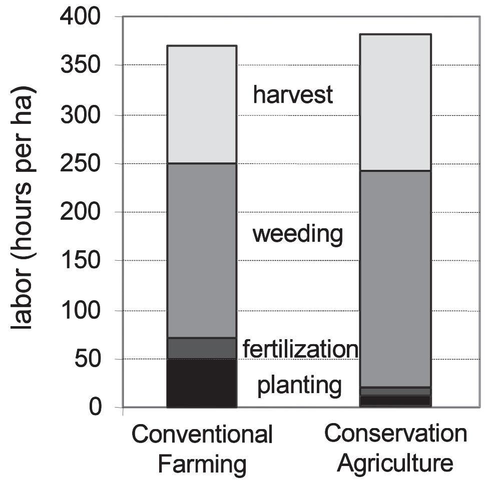


Figure 10.5. Labor requirements of conventional farming and conservation agriculture from an experimental site in Zimbabwe (after Siziba 2008).

Conservation Agriculture and the smallhold farmer

Rumley and Ong (2007) identified the greatest obstacle toward African smallholder compliance to Conservation Agriculture as the requirement for continuous soil cover with crop residues and mulch. They suggested the need for an African-style Conservation Agriculture that focuses upon reduced tillage and the use of organic inputs and fertilizers, and integrating these practices with water harvesting. In this way, most of the gains resulting from soil moisture conservation are retained and a large proportion of crop residues become available for other household purposes. They also assert that Conservation Agriculture must also be fostered through the dissemination of handheld planters and herbicide applicators. These authors further suggest that in areas with sufficient moisture, agroforestry and Conservation Agriculture are natural partners, particularly when prunings from nitrogen-fixing trees provide sufficient surface mulch to meet the system's soil fertility requirements. By making better use of limited moisture, providing nutrients through organic fertilizers and developing useful extension materials, Rumley and Ong (2007) assert suitably modified Conservation Agriculture can gain a foothold among small-scale farmers that would allow for further innovation and integration into smallhold farming practice.

The constraints to adoption of Conservation Farming by small-scale farmers may in fact be more fundamental than just competition for crop residues. Conservation Agriculture requires long-term planning and a commitment to agricultural resource protection. A new suite of skills are required in fertilizer and weed management and to execute these skills new farm inputs, particularly as herbicides, are required. In addition, specialized equipment must be purchased, calibrated and maintained. In most rural settings of Africa, the support infrastructure and policy will for transition to Conservation Agriculture is lacking. In many cases, community by-laws protect the rights of stubble grazing by livestock that interferes with adopters' attempts to establish continuous mulch cover, however, precedent exists for African farmers to protect their rights to mulch (Erenstein *et al.* 2008). Conservation Agriculture may offer longer-term economic and environmental benefits to small-scale farming, but the pathway to achieving these rewards is difficult and unclear. It will be extremely difficult to convince a poor farmer to abandon soil digging when a hoe is the only implement they know and own and that it is perhaps unfair to blame non-adoptors of narrow-mindedness (FAO 2008).

Conservation Agriculture was first developed for application by large mechanized farms and its relevance to smallhold farming in the tropics is tenuous, especially with regard to its central pillars; no-till, continuous surface cover and crop rotation. Tradeoffs between soil rehabilitation and manual weed control have escaped critical analysis and may place land managers in an impossible position from encroaching unwanted perennials (Knowles and Bradshaw 2007). Waterlogging of no-till soils is more likely to pose a problem in the semi-humid and humid tropics. Not only does high alternative demand exist for crop residues within the household (Powell *et al.* 2004), but termites may consume dried surface mulch within weeks and then turn their attention to crops. Small-scale farmers value livestock manure as soil inputs and lessening the importance of livestock for traction and diverting crop residues as feed may constrict their major role in nutrient recycling (Giller *et al.* 2009). Epigeic faunal populations that develop in surface litter are not necessarily beneficial and may pose hazards to crops and households alike. Intercropping and complex mixed cropping are far more common practices than monocropped rotations or improved fallows in the tropics, and this complexity is less suited to no-till seeding and herbicide weed control. Division of labor within Conservation Agriculture (Figure 10.5) may shift toward greater workload placed upon women (hand weeding) as tasks typically performed by men become reduced (animal plowing and weeding). We suggest that ISFM serves as an alternative, more practical approach toward achieving many of the benefits from Conservation Agriculture and that some of its principles, such as soil surface protection and precision application of inputs, may be readily embodied into site-specific ISFM routines.