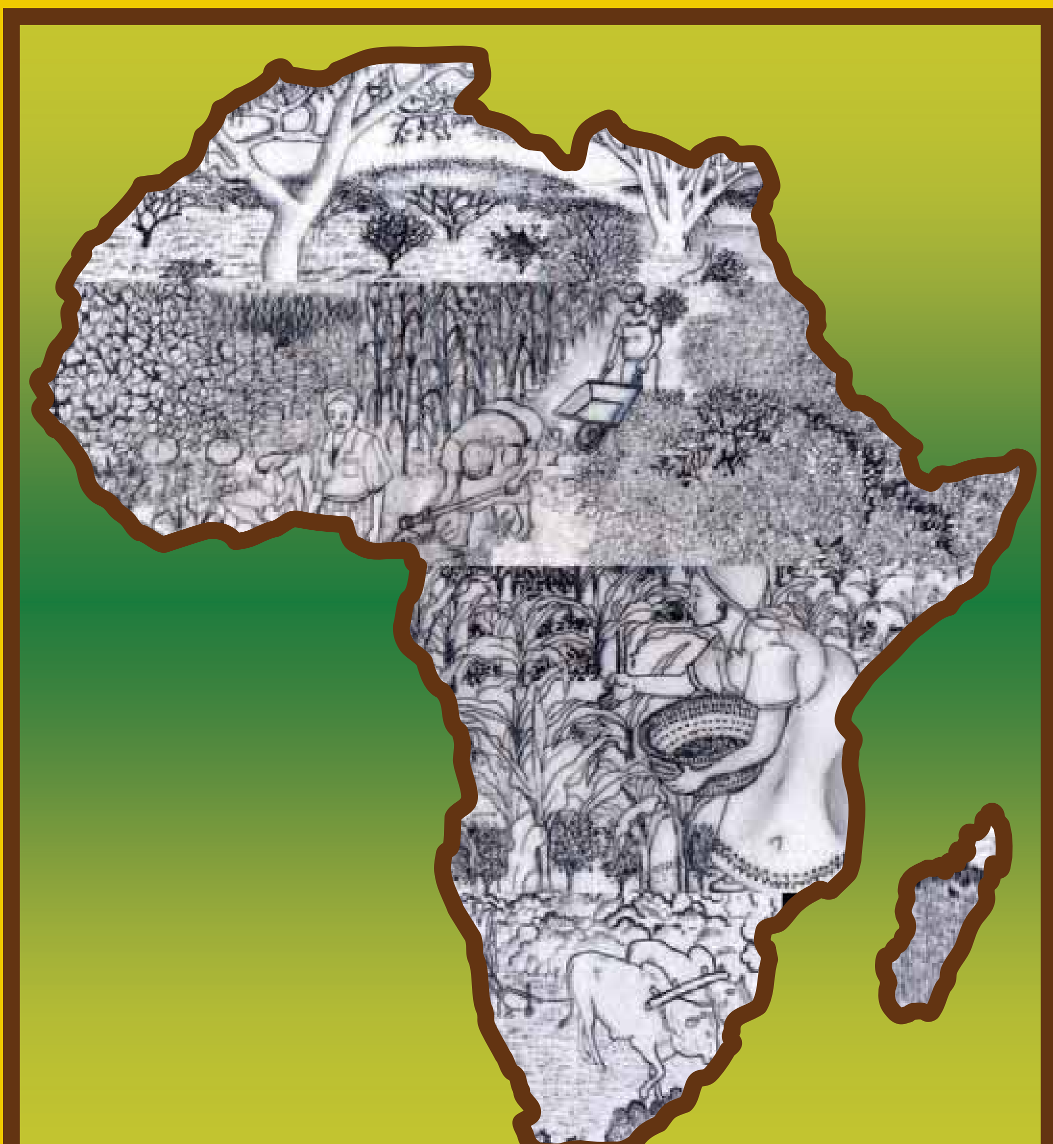
# Integrated Soil Fertility Management in Africa:

## Principles, Practices and Developmental Process



TSBF-CIAT

# Integrated Soil Fertility Management in Africa:
## Principles, Practices and Developmental Process

Edited by Nteranya Sanginga and Paul L. Woomer

Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture (TSBF-CIAT)

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**This book is dedicated to Spider Moghogo, K. Mulongoy, J. Robert Okalebo, Seth Danso and the other soil scientists in Africa who pioneered Integrated Soil Fertility Management before it was known as such and to Akin Adesina and John K. Lynam who helped so many young scientists follow their footsteps**

# Integrated Soil Fertility Management in Africa: Principles, Practices and Developmental Processes

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# Foreword

# A Call for Integrated Soil Fertility Management in Africa

*The soil nutrient losses in sub-Saharan Africa are an environmental, social, and political time bomb. Unless we wake up soon and reverse these disastrous trends, the future viability of African food systems will indeed be imperiled.'* Dr. Norman Borlaug, 14 March 2003, Muscle Shoals, Alabama, U.S.A.

Rising fuel and fertilizer prices, high rates of rural poverty, underdeveloped farm input and commodity markets and a declining human capacity for soil and natural resource research continue to exacerbate the situation described by Dr. Borlaug. As a result and on a more optimistic note, soil health issues and the relevance of soil fertility research are now impacting upon the agendas of policymakers and developmental agencies. For instance, the Heads of States at the African Fertilizer Summit conducted in Abuja, Nigeria during 2006 recommended that current fertilizer use in Africa be increased from the current average of 8 to 50 kg nutrients $ha^{-1}$ by 2015. In response, The Bill and Melinda Gates Foundation (BMGF) and the Rockefeller Foundation are investing in soil health as a component of the African Green Revolution (Annan 2008) being implemented through the Alliance for a Green Revolution in Africa (AGRA). The AGRA Soil Health Program is building a foundation for agricultural sector growth by restoring African soil fertility through improved land management and increased access to fertilizers that sustainably increase crop productivity by 50-100%. The African Green Revolution operates on the assumption that half of the huge yield gap existing between SSA countries and the developed world must be closed through improved soil nutrient management and accompanying field practices while the remainder resolved through widespread adoption of improved crop varieties. African farmers, therefore, need better technologies, more sustainable practices, improved seeds and fertilizers to increase and sustain their crop productivity, and to prevent further degradation of their agricultural lands.

During early 2007, BMGF commissioned the Tropical Soil Biology and Fertility Institute of CIAT (TSBF-CIAT) to develop a series of concept papers on Integrated Soil Fertility Management (ISFM). These reports were intended for the Foundation's use in designing an African Soil Health Initiative. In response to that challenge, TSBF-CIAT assembled a team of fifteen experts drawn from Africa and elsewhere to develop a series of concept papers on 1) overall ISFM approaches for Africa, 2) developing appropriate ISFM recommendations for small-scale farmers, 3) improving ISFM practices and building research capacities, 4) increasing farmers' access to soil fertility management inputs and 5) the relationship between soil fertility management and human nutrition. These reports were developed over four months and the final documents delivered to the Foundation in early May 2007, consequently influencing the design of their soil health strategy.

Recognizing the potential importance of this information to research and development interests in Africa, these concept papers have been compiled and expanded and into this book. The book's purpose is not only to improve understanding of soil fertility management in Africa, but to do so in a proactive manner that serves as a call for action This book describes the principles and practices of better managing soil fertility and sustaining crop productivity in Africa, but also the developmental processes necessary to propel ISFM into broader developmental and environmental agendas. In this way, this book not only captures current scientific knowledge of soil fertility management for use by agricultural researchers and educators, but also serves as a crossover publication for application by policymakers, development specialists and rural project managers at a time when the continent must respond to challenges posed by food shortages and continuing degradation of its agricultural resources. It is hoped that this book will contribute to more effective and widespread application of ISFM approaches and technologies, resulting in more productive and sustainable agriculture, improving household and regional food security and increasing incomes of small-scale farmers.

The approach advocated to improve the soil fertility status of African soils is embedded within the ISFM paradigm and will be achieved in large part through the increase in agronomic efficiency as fertilizer use grows with time. ISFM is the *application of soil fertility management practices, and the knowledge to adapt these to local conditions, which maximize fertilizer and organic resource use efficiency and crop productivity. These practices necessarily include appropriate fertilizer and organic input management in combination with the utilization of improved germplasm.'* Improving agronomic efficiency entails more intensive farmer management in areas such as maintaining mineral nutrient balance, correcting soil acidity, and making effective use of limited organic resources. Maximum benefits from ISFM practices and technologies can only be obtained within an enabling context, where such factors as farm input supply and produce markets, functional service delivery institutions, and progressive policies are in place. Translating this knowledge into practical land management strategies and empowering farmers through participatory technology development and adaptation is key to successful application of ISFM.

A broad and flexible approach to strengthening ISFM is envisaged which can result in large-scale impact within different agro-ecological zones over a relatively short time. Improving and disseminating ISFM in drylands through improved fertilizer placement, manure management and water harvesting is key within the Sahel, an area characterized by extreme poverty and episodic famine. Enhanced use of fertilizer within cereal croplands accompanied by maximum benefit from nitrogen-fixing legumes grown as intercrops or in rotation is an entry point for achieving food security and income generation in the moist savannas and dry woodlands of East, West and Southern Africa. Proven land management practices and, to a lesser extent, appropriate soil fertility products, are well established within these two agro-ecological zones of Africa, and it is only the lack of supportive policies and poor market development that impedes their widespread adoption. ISFM strategies appropriate to cassava, rice and banana production systems in the humid tropics are not as fully developed but investments in this area offer huge potential returns because significant gains in productivity of these crops are important for household food security and expansion of local and regional markets and trade.

Three accompanying developments are also necessary for the benefits of ISFM to become realized; improved capacity in farmer diagnosis and adaptive management of soil fertility constraints, greater access to farm input and commodity markets by small-scale farmers, and strategic policy adjustments that stimulate institutional and market response toward ISFM and its resulting crop surpluses. All the above cannot be realized without reviving and strengthening human and institutional resources. Recent reviews of the different stakeholders and partners involved in ISFM research for development in SSA point to the need to build capacity and to consolidate efforts at all levels from farmers to researchers and policymakers. To generate and deliver demand-driven knowledge and technologies, there is a need for a continent-wide strategy addressing ISFM that is supported by a Center of Excellence and networking platforms in SSA to foster partnerships between advanced research institutions, national agricultural research and extension systems, and the private sector.

Expanded funding for ISFM research adoption and scaling-up is critically needed given the urgency of addressing challenges posed by global climate change and food shortages on the continent. At the heart of that support must be a critical mass and diversity of soil management expertise throughout SSA. As the world grapples with the challenges of achieving food security it is crucial that foundations and government alike should invest at scale in reaching millions of farmers with ISFM technologies. The time for this is now. This book offers the way forward in achieving this goal.

Akin Adesina — August 2009
Vice-President, Alliance for a Green Revolution in Africa.

# Introduction

# ISFM and the African farmer

African agriculture stands at a crossroads. Either food security in Africa will remain elusive with isolated successes fuelling a sense of false optimism in an otherwise dismal situation or decisive action can be taken to assist small-scale farmers to grow more and more valuable crops. Excellent progress is being made in crop improvement and seed systems, and many crop diseases, particularly viruses and fungal leaf pathogens, no longer pose a major problem (DeVries and Toennissen 2001). Poor soil fertility and nutrient depletion continue to represent huge obstacles to securing needed harvests. Improving access to fertilizers is a necessary countermeasure, particularly when farmers develop skills in selecting which fertilizers are required and how to best derive benefits from their application. ISFM as defined in the Foreword represents a means to overcome this dilemma by offering farmers better returns to investment in fertilizer through its combination with indigenous agro-minerals and available organic resources. Disseminating knowledge of ISFM and developing incentives for its adoption now stand as the challenge before national planners and rural development specialists.

Better managing soil fertility is an imperative for sub-Saharan Africa. Pedro Sanchez (1997) reinforces this view by identifying soil fertility depletion on smallholder farms as the *"fundamental biophysical root cause of declining per capita food production in Africa"* and advocated more integrated problem-solving approaches. Despite these insightful observations, the situation has only worsened. We face more than an economic problem because this potentially explosive situation resulting from food insecurity threatens the very fabric of social stability in the poorest countries. Several technological breakthroughs have emerged in Africa over the past decade that, once effectively disseminated, offer the means to reverse this ominous picture. Never before has there been a more advantageous opportunity to reinforce the role of the agricultural research and development community in addressing the full suite of soil fertility, food production and land degradation problems in Africa.

Smallhold farming systems in Africa are undergoing a profound transformation from subsistence farming to mixed-enterprise, market-oriented agriculture. This transition is in some cases abrupt, as when smallholders are recruited into large out-grower schemes, but in most cases it is subtle as households more fully recognize that their household needs cannot be satisfied by farming in isolation, and they make stepwise adjustments to improve their production and marketing skills (Woomer *et al.* 1998). A brief account of the origins and history of smallhold farming allows this transformation to be better placed into perspective.

Smallhold farming, where a large household permanently and intensively cultivates a small area of land, is a recently-developed phenomenon. Africa, especially East and Southern Africa, has undergone a series of pastoralist migrations from West and northern Africa (Oliver 1982). Once new lands suitable for agriculture were secured, these migrants farmed relatively small portions of land, and practiced long-term, grazed fallow rotation as a means of replenishing land productivity. Farmers cultivated a wide variety of indigenous crops and gathered traditional green vegetables and indigenous fruits. Livestock were viewed as wealth and complex patterns of communal grazing and gift giving developed around them. As population densities increased, a larger proportion of land was placed into cultivation and fallow intervals decreased until, in the most densely populated areas, communal grazing ceased.

At the earliest stages of European and Arab contact, new crops were introduced from tropical America and rapidly adopted by cultivators, particularly maize, beans, groundnut and cassava, allowing for greater intensification of land use. Interrupting this process in many parts of East, West and Southern Africa was the invasion of colonialist farmers who displaced Africans from the best agricultural lands and, in many cases, forced them to become labourers on large plantations (Odingo 1971). This invasion was short-lived, ending for the most part with independence and leaving behind a mixed legacy of new cash crops, farming methods, infrastructure and land tenure. On the other hand, many traditional crops and farming practices were lost and land reallocation was somewhat irregular. It is within this backdrop that today's small-scale farming households developed.

Newly-independent African governments sought to jumpstart their economies into the 20th Century through the development of parastatal boards regulating agriculture and infant industries (Eicher 1999). These boards were intended to improve commodity markets and provide a basis for taxing agriculture. Their highest priority was to reinforce export crops, such as coffee and tea, as a means of securing foreign currency for industrial development and many of the basic needs of smallholders became overlooked in the process. This lack of commitment to the poorest is partly responsible for the failure of the Green Revolution to take root in Africa in the 1970's (Okigbo 1990) and led to chronic food insecurity and episodic famine in the following decades.

African governments established agricultural extension services, marketing boards, farmers' associations, credit schemes, faculties of agriculture and national research institutes, principally toward the benefit of richer farmers. The services of these bodies were weakened during the economic crises of the 1980s when budget deficits and inflation prevailed. Many parastatal boards fell into mismanagement as well (Alexandratos 1997). Donor institutions imposed structural adjustment programs that resulted in dismantling or privatizing parastatal bodies and liberalizing the agricultural economy. Unfortunately, many of these reforms did not achieve the desired growth as private sector investment failed to materialize, leaving little to fill the rural services vacuum (Eicher 1999).

During these four decades, little changed for the smallhold farmers except their numbers increased greatly, their farm size diminished, their resource base degraded and seasonal food shortages intensified. Governance has improved in Africa as a result of democratization and market reform during the 1990s, but these gains did not result in the expected benefits among small-scale farming households, and in many cases the lives of the poorest farmers worsened. Some smallholders grew demoralized, others migrated to urban areas but the majority sought to make the best of their difficult situation.

The future of small-scale farming households largely rests in their ability to rapidly seize new production and marketing opportunities and the corresponding actions by national planners and development agencies to better empower farmer collective action. Hindrances beyond smallholders' control persist, notably weak rural road and utilities networks that in turn result in high costs of farm inputs and marketable crop surpluses. Agricultural extension is sporadic at best and attempts at extension reform are largely ineffective. Much of this dilemma is related to improperly translated training-and-visitation extension models because of the large numbers of extension clients resulting from increasingly smaller farms. Even the frontline extension agents lack sufficient educational materials and financial resources to assist their nearest clients (Lynam and Blackie 1994).

Several signals of real advances and promise of improvement in the lives of small-scale farming households exist. The ominous, decades-long trend of agricultural stagnation in Africa may have ended based upon steady improvement in crop-based agricultural growth rates over the past decade (Omamo 2006). Other real advances include greater access to improved crop varieties, better soil and pest management (Conway and Toenniessen 2003), rapid growth and expansion of services to members of farmer associations and the emergence of out-grower networks addressing specialty export markets (Stringfellow *et al*. 1997).

In order to complete these gains, rural prosperity in Africa requires that land managers make flexible use of ISFM knowledge and technologies in order to produce and market more food while improving their agricultural resource base (Vanlauwe *et al*. 2006). ISFM knowledge is not rigid, rather it involves adjustable application of basic principles in land management. Important features of ISFM with particular relevance to African small-scale farming systems include 1) the judicious application of purchased fertilizers, 2) the efficient management of available organic resources, 3) wider integration of nitrogen-fixing legumes into cropping systems and 4) the conservation of soils and their biota and organic matter. ISFM practices are derived from combining these elements in a manner that is both site-specific and locally acceptable. Amplifying knowledge of ISFM requires capacity building from the grassroots through the professional levels. Furthermore, developing better land management technologies necessarily involves private sector participation in designing and distributing farm inputs.

Our knowledge of Africa's soils is relatively small compared to the hundreds of millions small-scale farmers who make their living from its management (Table 1). In our attempts to fill this knowledge gap, however, numerous practical achievements have occurred, often with land managers taking the lead. The management of available organic resources by smallholders seeking to diversify their operations and address new markets often demonstrates an intuitive understanding of nutrient recycling (Giller 2002). Most African farmers make innovative use of field and farm boundaries, and collect useful organic materials from outside their farms, often by necessity, and then incorporate them into their major farm enterprises, particularly cereal-based cropping and livestock rearing (Woomer *et al.* 1999). Despite their high cost and competing demands for scare cash, farmers are learning to access mineral fertilizers and to use them in a judicious manner. It is within this agricultural setting that ISFM is taking hold in Africa through the more effective combination of organic and mineral inputs to soil and directing them toward more profitable use.

The redirection of soil management practice is best conducted in conjunction with the adoption of improved crop varieties that have been specially bred to meet rural household needs (DeVries and Toennissen 2001). In this way, new cropping systems that involve higher yielding staple foods grown in conjunction with new and improved legumes in rotations and intercrops can raise the living standards of African small-scale farmers while improving the soils upon which their future depends. The challenge now before the research and development community is how to replicate and expand isolated success in ISFM in a manner that rapidly attracts a variety of land managers and empowers even the poorest farming households to become innovative adaptors (Woomer *et al.* 2002).

While the goal of ISFM, to deliver nutrients to crops in a resource-, labor- and cost-effective manner remains constant, the means to achieve ISFM varies within different agro-ecological

Table 1. Selected characteristics of agro-ecological zones in sub-Saharan Africa. Lowland areas are <800 meter above sea level (masl), mid-altitude areas between 800 and 1200 msal and highland areas >1200 masl. Lengths of growing period are <150 days for dry areas, 150-270 days for savannas and >270 days for forest areas. After: FAO (1995); FAO/IIASA (2000); FAO/IIASA (2002).

| Agro-ecozone (% of the area) | Appropriate ISFM Technologies | Major soil orders (FAO system) | Major nutrient-related constraints |
|---|---|---|---|
| Lowland dry savanna (36%) | Micro-dosing, Agro-pastoral interactions, Rock phosphate | Arenosols, Lithosols, Regosols | Low available soil P, soil acidity, low water holding capacity |
| Lowland moist savanna (17%) | Cereal-legume rotation and intercrops; Conservation Agriculture | Lixisols, Ferralsols | S, Zn deficiency under intensive cultivation, low available N and P |
| Lowland humid forest (15%) | Cassava-legume intercrops, understorey & lowland rice management | Ferralsols, Acrisols | Soil acidity, low available soil P |
| Mid-altitude moist savanna (7%) | Cereal-legume rotation and intercrops; Conservation Agriculture, slope management | Ferralsols, Nitisols | Soil acidity, low available N and P |
| Highland moist forests (7%) | Intercrops and rotations, slope management | Ferralsols, Andosols | Soil acidity, low available soil P |

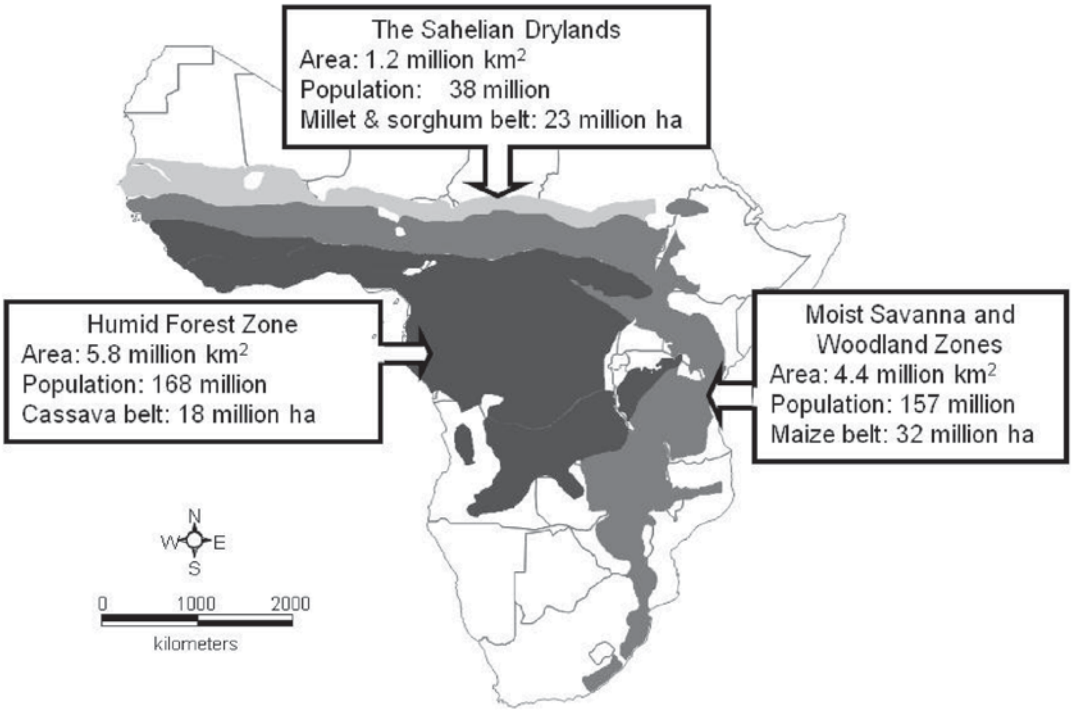



Figure 1. A summary of the characteristics of the zones and cropping systems warranting investment in ISFM.

zones (AEZs) and cropping systems. Different ISFM technologies are required to address the range of soil characteristics occurring in various AEZs in sub-Saharan Africa (Table 1). The coverage and additional information on some of these zones is presented in Figure 1.

Different soil fertility management technologies may be grouped in terms of effectiveness and potential for widespread adoption (Figure 2). Technologies appearing in Quadrant A (Figure 2) have reduced potential in terms of their productivity gains and adoption by small-scale farmers. Vermicomposting is practical at an industrial scale for the production of organic fertilizer and potting mixture, but the domesticated epigeic earthworms are not widely available and their high-quality organic feeds have more immediate alternative uses. Municipal and human wastes may also be transformed into organic fertilizers but they are bulky and their use may pose public health concerns. Lengthy experience with alley farming, where crops are grown between alternating rows of pruned trees, suggests that root crops and sandy soils are poorly suited to this system. Live fences on small plots or farms often result in excessive above- and below-ground competition with field crops. Despite these disadvantages, these technologies may prove useful under many circumstances, particularly the use of vermicomposting and municipal wastes in urban agriculture (see Chapter 4), but it is not otherwise advised to build a major soil fertility management program around them alone.

Technologies in Quadrant B (Figure 2) are attractive to small-scale farmers but usually do not result in farm-level benefits. Use of low quality crop residues or insufficient and improperly handled livestock manures in absence of mineral fertilizers provide too few nutrients for substantial gains in field crop production (see Chapter 4). Domestic composting may improve the nutrient concentration of organic resources, but its supply is usually insufficient and best directed toward home gardens or high value crops. Rotating or intercropping cereals and legumes produces crops needed by the household but production levels are usually low unless some form of nutrient replacement is practiced. In the same way, the production of stress-tolerant and nutrient-efficient crop varieties provides little in degraded soils, but they respond well to improved soil fertility management (see Chapter 15). The technologies in this quadrant

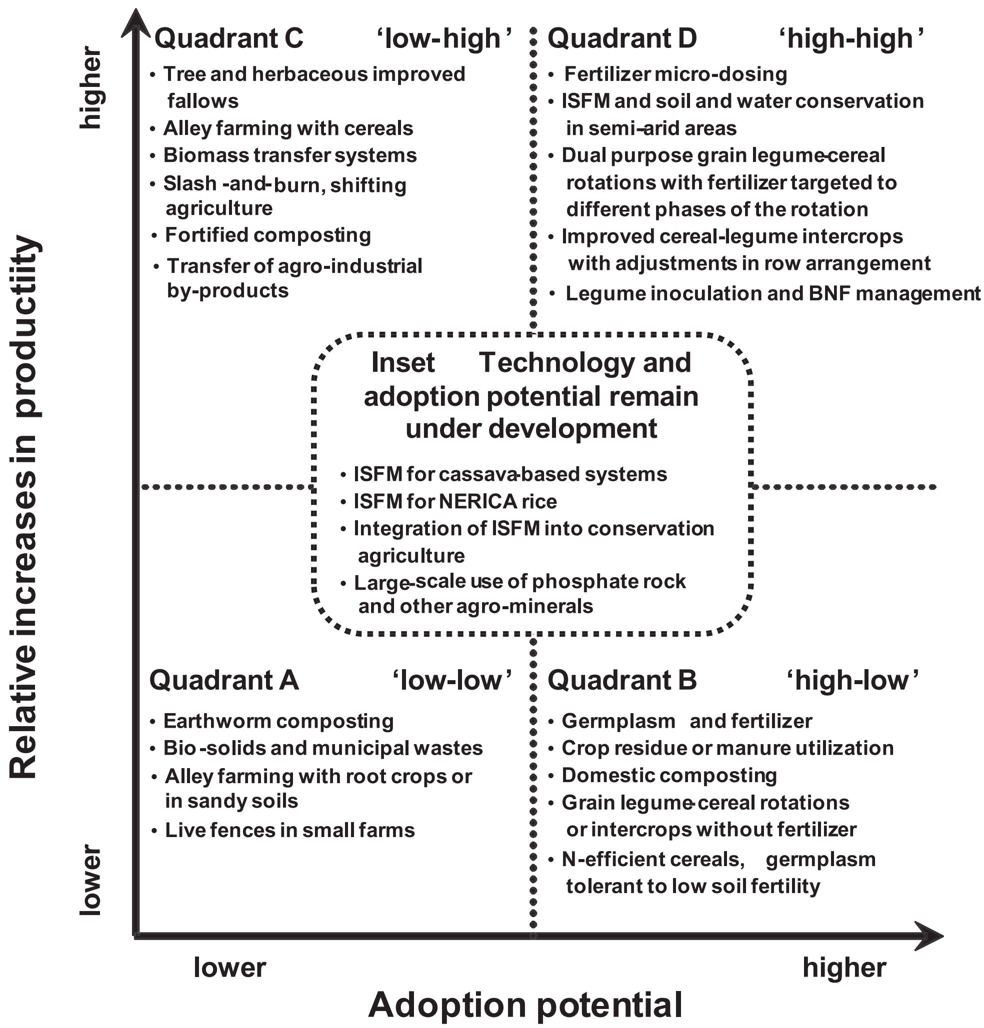



Figure 2. The relative adoption potential and contribution to soil fertility enhancement for various tested soil fertility management interventions. Adapted from A. Adesina (personal communication).

must not be dismissed as failures because they remain attractive to farmers, rather strategies must be employed to integrate them with more productive resource management approaches (see Chapter 11).

Practices presented in Quadrant C (Figure 2) have proven abilities to increase nutrient supply and improve both crop productivity and nutrient use efficiency, but they remain unattractive to farmers for a variety of reasons. Improved fallows require that lands be withdrawn from crop production, labor be redirected and that farmers invest in relatively expensive seed. Alley farming with nitrogen-fixing trees and cereals works, but requires intensive management and the sacrifice of some cropland. Biomass transfer systems, where organic resources are recovered, transported and applied, redirects nutrients to croplands but at the expense of other areas and requires large commitment of labor at a time with competing demands (see Chapter 4). Shifting agriculture, especially slash-and-burn, produces short-term benefits but at much greater environmental cost and is feasible only where population pressures are extremely low (see Chapter 9). Fortified composting involves the addition of fertilizers, agro-minerals and manures to bulky crop residues, and their partial decomposition, resulting in a high quality organic fertilizer, but requires hard work, cash investment and time to transform these materials that could be otherwise applied directly during field operations (see Chapter 4). This practice is, however, extremely practical in higher value horticultural enterprises. Similarly, agro-industrial wastes are useful as soil inputs, mulch or compost ingredient and are often free for the taking, but their bulk and difficulties in transport make them unavailable to most farmers (see Chapter 6). Indeed, the challenge to make more practical advantage of technologies appearing in Quadrant C is to target them to the correct smallholder clients while reducing their comparative disadvantages to others.

Technologies capable of delivering rapid benefits to large numbers of farmers in sub-Saharan Africa are presented within Quadrant D (Figure 2). Fertilizer micro-dosing involves spot placement of fertilizers, sometimes timed to rainfall in split applications. In semi-arid areas, ISFM practices may be strategically combined with water harvesting, usually through the creation of mini-catchments within the field (see Chapter 7). Combining cereals and grain legumes through rotation, intercropping and relays, and proving these crops with strategically applied mineral fertilizers and organic inputs are a key to ISFM and food security in Africa (see Chapter 6). In the case of crop rotations, additional information is required on optimal crop sequencing, and for intercropping, adjustments must be made in row spacing, orientation and crop combinations (see Chapter 8). In many cases, biological nitrogen fixation by field legumes can be increased through inoculation with elite strains of their microsymbiont rhizobia made available to the host through improved delivery systems (see Chapter 5). Much of this book is devoted to describing the refinement and dissemination of technologies falling within this quadrant.

Technologies with equally large potential but require further understanding or development before comprehensive ISFM packages may be built around them occur in the Inset of Figure 2. Management strategies for cassava and rice will certainly require mineral fertilizers and greater reliance upon nitrogen-fixing legumes, but additional research is needed before site-specific management practices are formulated (see Chapter 9). Conservation Agriculture shares many common features with ISFM, however, it was designed around large-scale mechanized agriculture and difficulties exist in applying its more restrictive provisions to small-scale agriculture (see Chapter 10). The larger-scale mining, processing and distribution of indigenous agro-minerals is an indispensable component of rural development in Africa and in some cases these materials are already being used as a replacement for more expensive, imported mineral fertilizers. Most agro-mineral deposits remain undeveloped or under-utilized, however, and coordinated efforts are required to design local, national and regional strategies for their better deployment (see Chapter 3). Again, substantial portions of this book address how to unlock the potential of technologies and materials belonging to this category. It is important to note that all of the technologies presented in Figure 2 have important roles within various farming systems in Africa and their refinement and adoption can contribute positively to site-specific application of ISFM.

## Practical examples of ISFM

Two practical examples illustrate how ISFM works and can be improved upon. In West Africa, for example, farmers have adopted the micro-dose technology (Figure 2) that involves strategic application of small doses of fertilizer (e.g. 4 kg P $ha^{-1}$) and planting seed of improved crop varieties (Tabo *et al.* 2006). This rate of fertilizer application is only one-third of the recommended rates for the area. As a result of adoption, micro-dosed grain yields of millet and sorghum were increased by between 43 and 120% in pilot areas of Burkina Faso, Mali and Niger**.** The incomes of farmers using this practice improved by 52 to 134%. Small amounts of fertilizers are more affordable for farmers, give an economically optimum (though not technically maximum) response, and if placed in the root zone of these widely-spaced crops rather than broadcast, result in more efficient nutrient uptake (Bationo and Buerkert 2001). In addition, the number of farmers using fertilizers following introduction increases. This success story has shown that adoption of micro-dose technology requires supportive and complementary innovation and market linkage. Production gains of millet and sorghum are obtained through the combination of micro-dosing in conjunction with water harvesting through the establishment of *zaï* pits (small, shallow water catchments) and the placement of manure, crop residues and composts into each pit (see Chapter 7). Accompanying soil conservation methods include half-moon furrows, stone bunds and tied ridges which conserve water and increase nutrient use efficiency. These measures extend the favorable conditions for soil infiltration after runoff, and the pits are particularly beneficial during more severe storms when the organic inputs absorb excess water and act as a subsequent moisture reservoir for the crops (Reij and Thiombiano 2003). This approach also restores crusted and compacted soils as well. This ISFM technology is being rapidly adjusted and adopted in the Sahel and has equal potential in other dryland farming areas.

Another example is drawn from the Guinea savanna of West Africa where improvement in the use of fertilizer nitrogen is achieved through the addition of organic inputs to soils. A straightforward series of managements was installed at several locations with sandy soils and low soil nitrogen and organic matter where 90 kg $ha^{-1}$ of nitrogen was applied as urea fertilizer, farmer-available organic resources or an equal combination of both (Vanlauwe *et al.* 2001a). A basal addition of phosphorus fertilizer (30 kg P $ha^{-1}$) was included within all managements. Organic resources varied between sites depending upon their availability, were largely composed of tree leaves and twigs but also consisted of livestock and green manure at some locations.

Mineral N applied as urea at 90 kg N resulted in much higher yields than when the same amount of N was applied as a mixture of either surface mulched or incorporated organic inputs (Figure 3). When the two materials, mineral fertilizer and organic inputs (OI) were combined, however, strong positive interactions occurred, with maize yields comparable to those achieved from twice the level of mineral fertilization. This effect was mainly attributed to greater fertilizer use efficiency resulting from improved soil moisture conditions but contributions from mineralized nutrients other than N and P cannot be excluded. The nitrogen uptake from urea (15 to 43%) was much greater than that of the applied organics (8-10%), although the urea N alone provided relatively low agronomic use efficiency (13 kg grain per kg N). Improved moisture relations are also suggested by performance of maize in the surface mulched compared to the

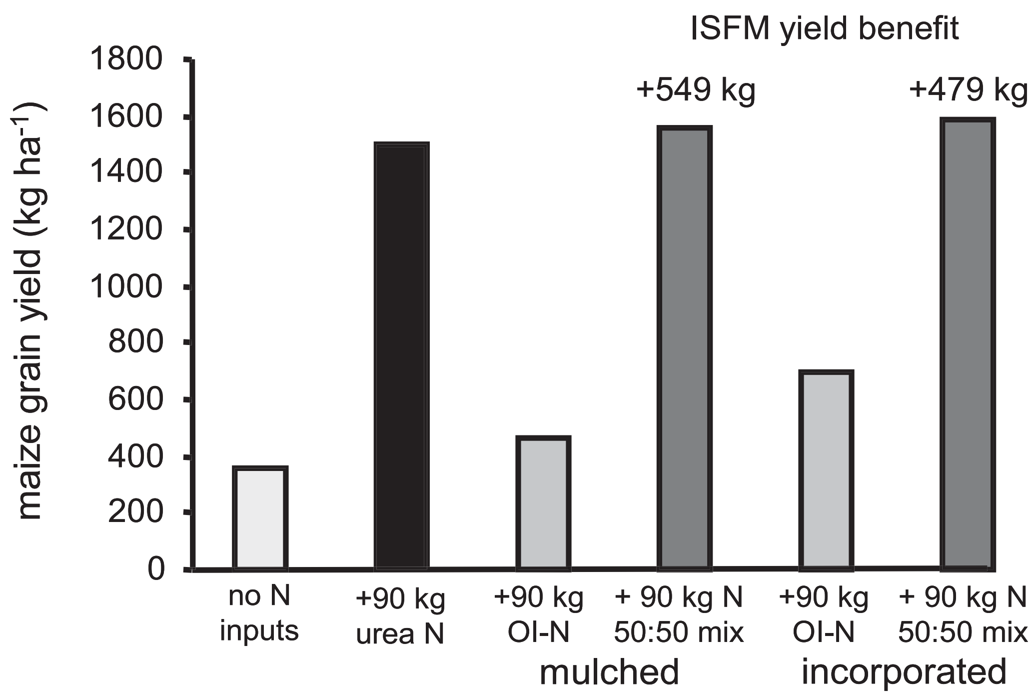



Figure 3. Interactions between mineral fertilizer and farmer-available organic inputs (OI) result in greater nutrient use efficiency (after Vanlauwe *et al.* 2001).

incorporated management (Figure 3). Overall, practicing ISFM required $56 less purchased inputs, involved several hours more field labor and resulted in an additional 514 kg maize grain $ha^{-1}$ worth about $136. This example illustrates how crop yields may be improved through the application of relatively small amounts of mineral fertilizers combined with organic resources, supporting the feasibility of reducing fertilizer recommendations to smallhold practitioners of ISFM (see Chapters 2 & 12). While this example is drawn from experimental evidence in Benin, Cote D'Ivoire, Nigeria and Togo, any farmer may obtain the benefits of interactions between mineral fertilizers and organic inputs through the recovery of vegetation along farm boundaries and its application to croplands.

## Realizing ISFM in Africa

The strong potential for achieving greater institutional involvement in soil fertility management, and extending needed technologies to more farmers greatly assists in targeting future investment in ISFM. Currently, the level of success of these practices is modest for a number of reasons: 1) livelihood strategies are influenced by many other factors besides ISFM, making ISFM-specific success less visible, 2) developments in breeding have a stronger breakthrough character because dissemination is more rapidly available and visible, 3) successes in ISFM are hard to come by since the Structural Adjustment Programs made fertilizer use unattractive to many farmers for several years, and 4) research and development efforts in the past lacked clear and consistent monitoring and evaluation tools that assess soil management capabilities. Success must be expressed by impact indicators, such as yield increases, increased fertilizer sales, numbers of ISFM adopters and improved agronomic efficiency of applied nutrients. The ISFM technologies presented in Figure 2 are useful to formulate strategies for intervention and direct future investment (see Chapters 14 and 19).

One of the greatest strengths of ISFM is its ability to integrate local suitability, economic profitability, adoptability, and sustainability in developing improved land management recommendations. Constraints to improved targeting of soil fertility input recommendations in SSA include the use of over-generalized blanket recommendations that do not take into consideration farmers diverse socio-economic and biophysical conditions, misdirected soil and crop management by farmers, lack of sufficient knowledge, limited access to responsive varieties, low and variable rainfall, limited access to stable produce markets, limited financial means and poor access to credit (see Chapters 2 & 12). If we assume for the moment that the degree and types of nutrient limitations are recognized and that technologies to ameliorate these conditions are identified, then the next important step is to devise strategies that facilitate the delivery of technologies to needy farmers. These technologies must be packaged into products and field operations that are recognizable, available and affordable to farm households (see Chapter 14). Policy interventions and marketing strategies can improve farmers' access to improved technologies but these will remain under-utilized if they appear over-priced or are perceived as risky (Chapter 19 and 20). The following points relate to the understanding and promotion of ISFM technologies among farmers at the grassroots level.

1. **Combine the strategic application of fertilizers and farmer-available organic resources in a manner that increases nutrient use efficiency and makes fertilizer use more profitable.** Fertilizer use must not be viewed as a standalone option for the management of soil fertility and the application rates recommended to farmers are too often beyond their means (see Chapter 2). Combining agro-minerals and organic resources also accelerates nutrient release (see Chapter 3). The elegance of ISFM is that it improves the efficiency of mineral fertilizer use through its combination with organic resources while producing longer-term beneficial environmental impacts (see Chapter 5). Organic resources vary in their nutrient contents and mineralization characteristics, and some even result in short-term immobilization of soil nutrients if not applied properly, so ISFM practitioners concerned with

the best use or processing of different quality materials require specialized knowledge (see Chapter 4).

2. **Optimize improved germplasm, water use efficiency and agronomic practices within new soil fertility management recommendations.** Studies have shown that introduction of a cash crop, such as cowpea, soybean or high value vegetables, into a cropping system can greatly boost the use of fertilizer by smallhold farmers and increase yields of succeeding food crops. The Oslo Conference on the African Green Revolution highlighted the role of crop diversification in optimizing farmer returns and as a principle of risk management to protect those returns. In addition, new crop varieties have been bred recently for drought tolerance, pest and diseases, and adaptation to low soil fertility and there is need to accelerate their adoption by smallhold farmers through ISFM practices.

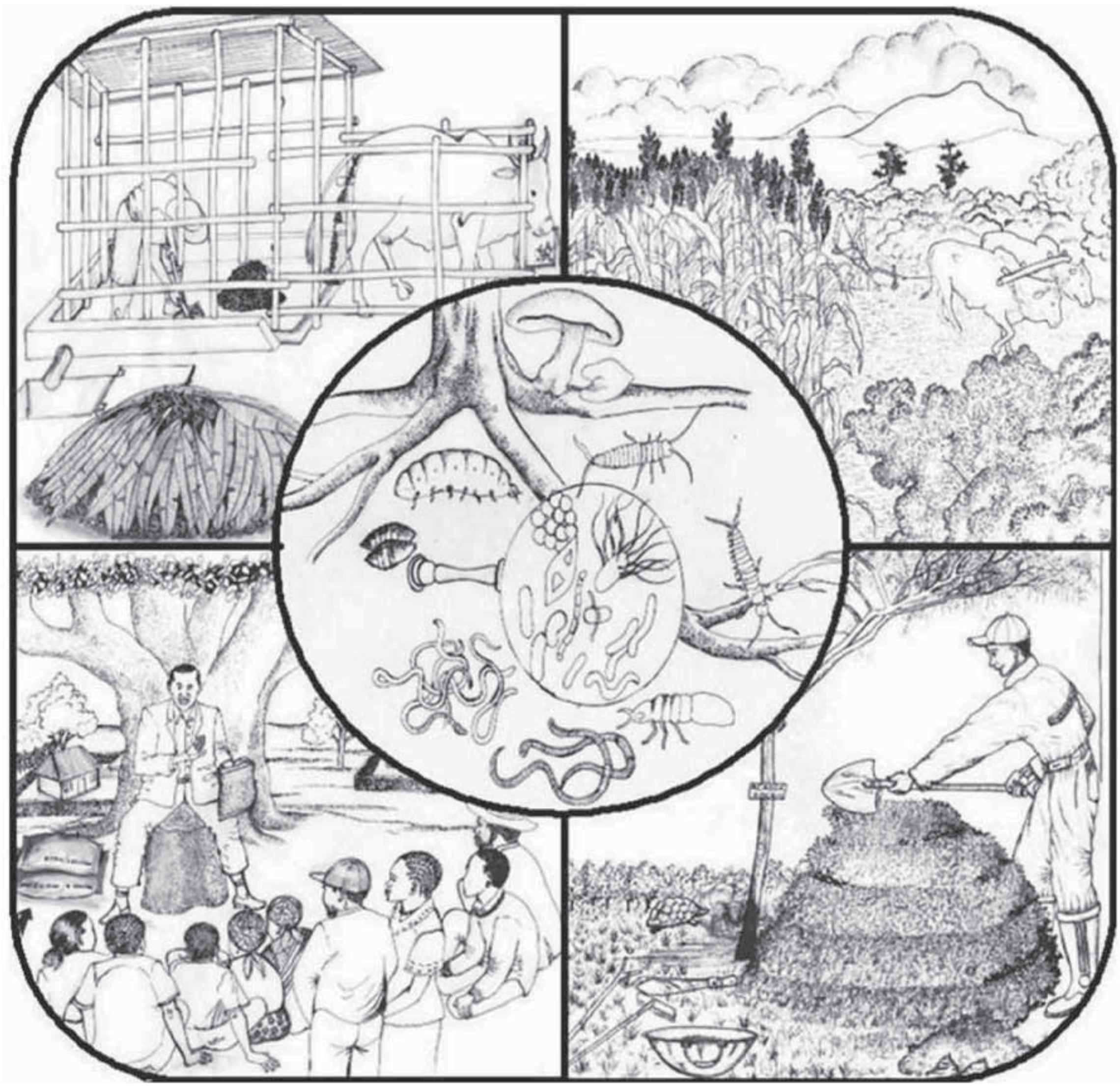
3. **Keep recommendations and demonstrations simple.** On-farm trials and community demonstrations that are designed by agricultural scientists are too often overly complex, distracting farmers from their intended messages. ISFM is necessarily knowledge intensive and special attention must be placed upon capturing its findings into simplified field operations. Researchers who install large, replicated, randomized experiments in farmers' fields that are intended to host instructional field days risk confusing their clients. More information and better feedback is conveyed through simpler roadside field demonstrations and on-farm technology trials (see Chapters 11, 12 & 13).

4. **Work through existing organizations and networks.** Working with existing farmer associations and their umbrella networks to promote ISFM use offers several advantages. To a large extent, these farmer groups formed as a means of better accessing information and technologies in absence of adequate support from agricultural extension. These groups represent a ready-formed audience for technical messages, will collectively undertake independent technology evaluation and provide necessary feedback on the technologies (see Chapter 18). Larger organizations offer farm input supply services to their members, allowing them to purchase fertilizers in bulk or on credit, and pass savings to members. Farmer groups provide peer support to members, allowing them to undertake new and more complex field operations and investments. Other stakeholders, particularly farm input suppliers, also deserve attention during the planned promotion of ISFM products (see Chapters 6, 14 & 20).

5. **Adhere to market-led and value chain addition paradigms.** Improved profitability and access to market can motivate farmers to invest in new technology, particularly the integration of improved crop varieties and soil management options. This observation is based in part upon the disappointing past experiences of developing and promoting seemingly appropriate food production technologies, only to have them rejected by poor, risk-adverse farmers unable or unwilling to invest in additional inputs (see Chapters 19 & 20). When working in the market-led mode, agronomists will no longer assume that additional produce resulting from technical adoption will necessarily benefit the household, nor will economists assume that demand created through market innovations will automatically be filled. Agricultural value chains place farm planning, field operations and produce marketing into a holistic context that permits the innovations necessary to improve farming enterprises, including farmer's investment in ISFM products, to be more readily identified and compared (Sanginga *et al.* 2007).

# Part I

# Principles of ISFM



# Chapter 1. ISFM as a strategic goal

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

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

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

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

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

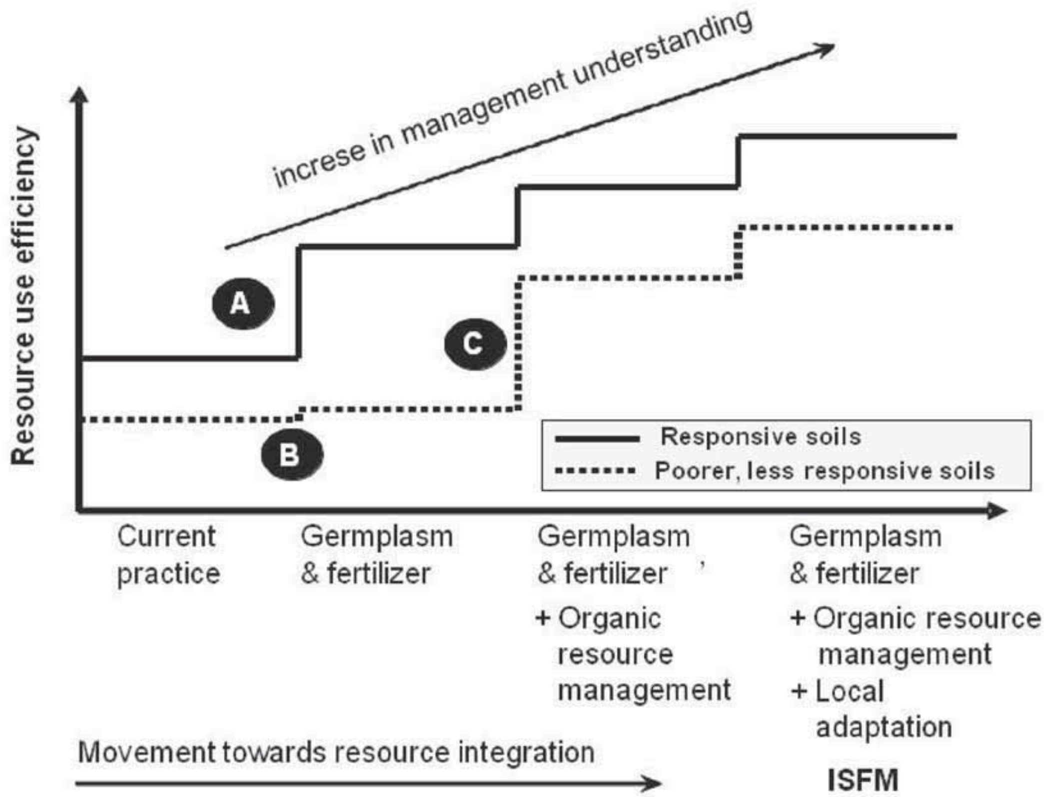



Figure 1.1. Conceptual relationship between the efficient use of resources as one moves from current practice to achieve ISFM.

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

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

**Fertilizer as an entry point for ISFM**

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

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

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

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

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

### The advantage of integrating management approaches

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

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

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

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

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

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

**Strategic objectives and measurable indicators of ISFM**

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

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

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

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

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

**Key considerations in devising ISFM strategies**

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

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

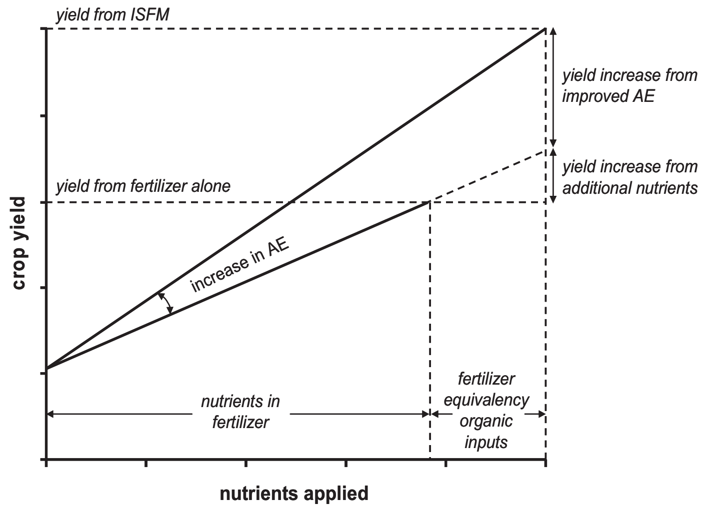



Figure 1.2. Conceptual diagram representing the yield increase from improved agronomic efficiency (AE) of fertilizer and organic resource addition (after Vanlauwe et al. 2001).

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

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

## The Importance of Agronomic Efficiency

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

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

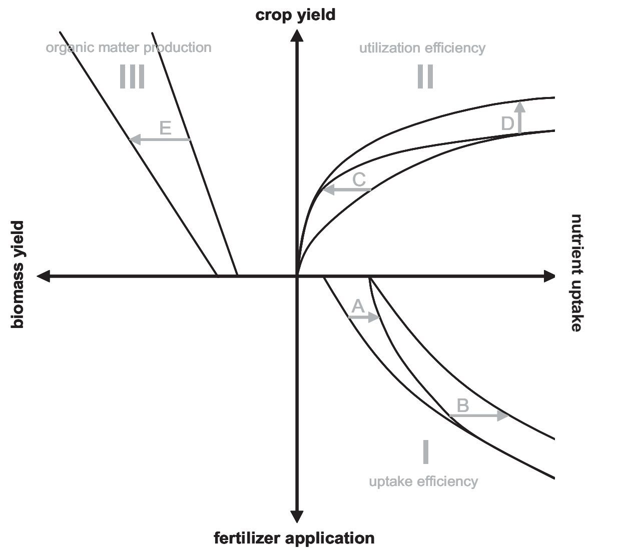



Figure 1.3. Conceptual diagram representing relationships between fertilizer application, nutrient uptake, crop yield and biomass production (from Van Keulen, 1982).

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

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

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

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

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

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

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

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

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

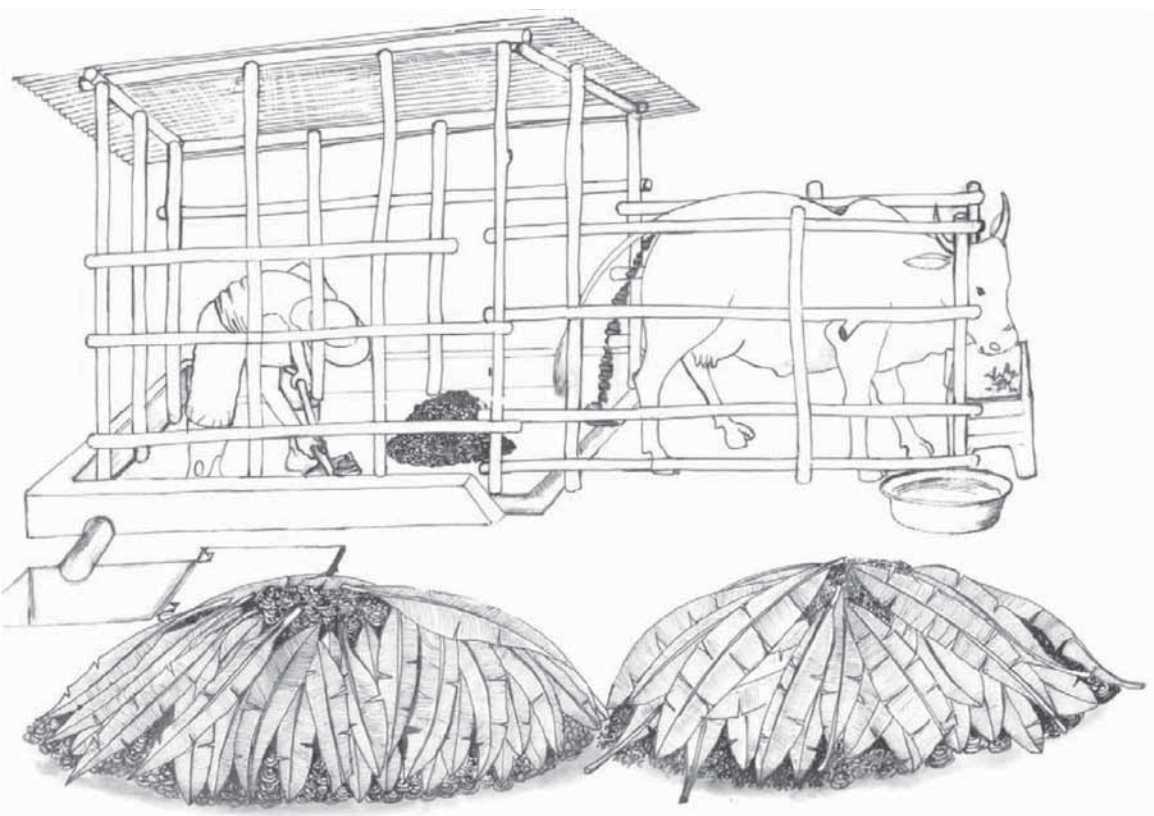
In conclusion, ISFM aims at effective input use by combining a number of nutrient sources and process regulators. ISFM practices involve 1) judicious use of mineral fertilizer and agro-minerals in terms of their form, placement and timing of application, 2) management of crop

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

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

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

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



# Chapter 2. Fertilizer management within ISFM

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

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

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

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

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

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

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

[1] not including South Africa.

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

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

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

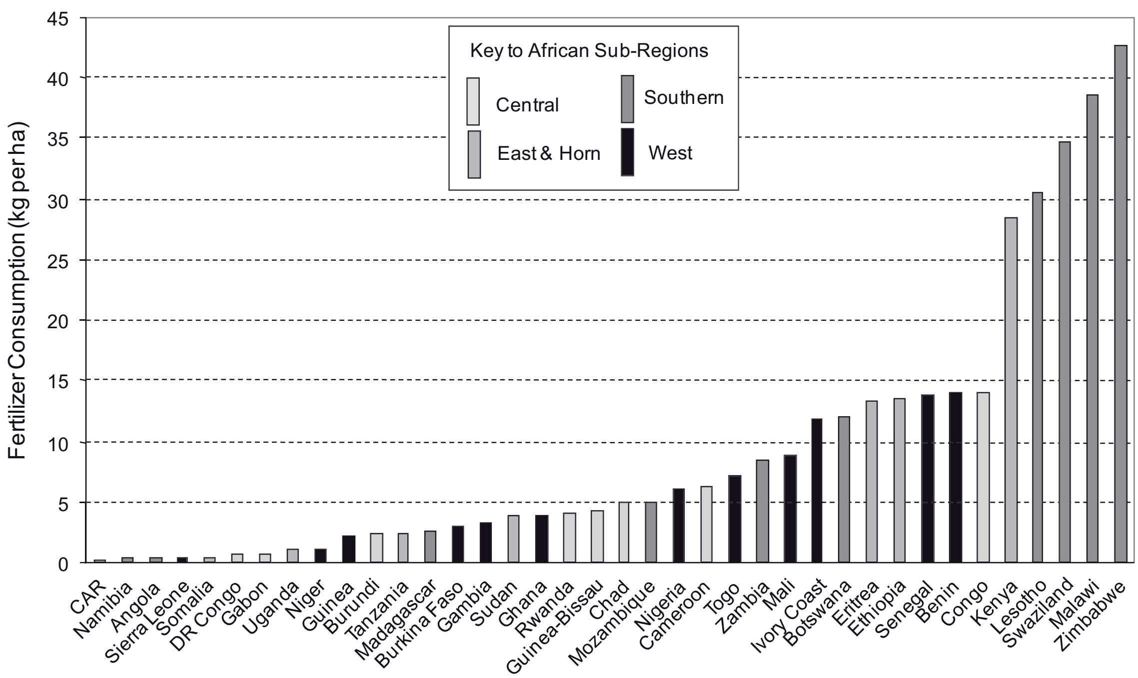



Figure 2.1. Fertilizer consumption in 38 nations of sub-Saharan Africa (FAO-STAT 2004)

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

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

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

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

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

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

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

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

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

Several factors constrain our current understanding of fertilizer adoption and use by small-scale farmers (Fujisaka 1994). Limited information is available on links between fertilizer use and soil management, especially tillage systems, and how fertilizers may be better incorporated. Women's poorer access to farm inputs, capital and credit requires greater understanding before gender can be factored into ISFM recommendations (Gladwin *et al.* 1997). There is lack of consistency in

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

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

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

fertilizer use data for different regions and countries and at finer scales, particularly 1:50,000 where individual farms may be distinguished. Role and effectiveness of extension services varies between countries and farmers' response to weak extension is not well characterized. Off-farm income allows investment in fertilizers, but household willingness to do so is not well understood. Social and cultural factors have a strong influence on farm practice, and these must be better described and interpreted within the context of targeting and recommending fertilizers.

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

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

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

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

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

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

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

**Availability, quality and utilization of mineral fertilizer**

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

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

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

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

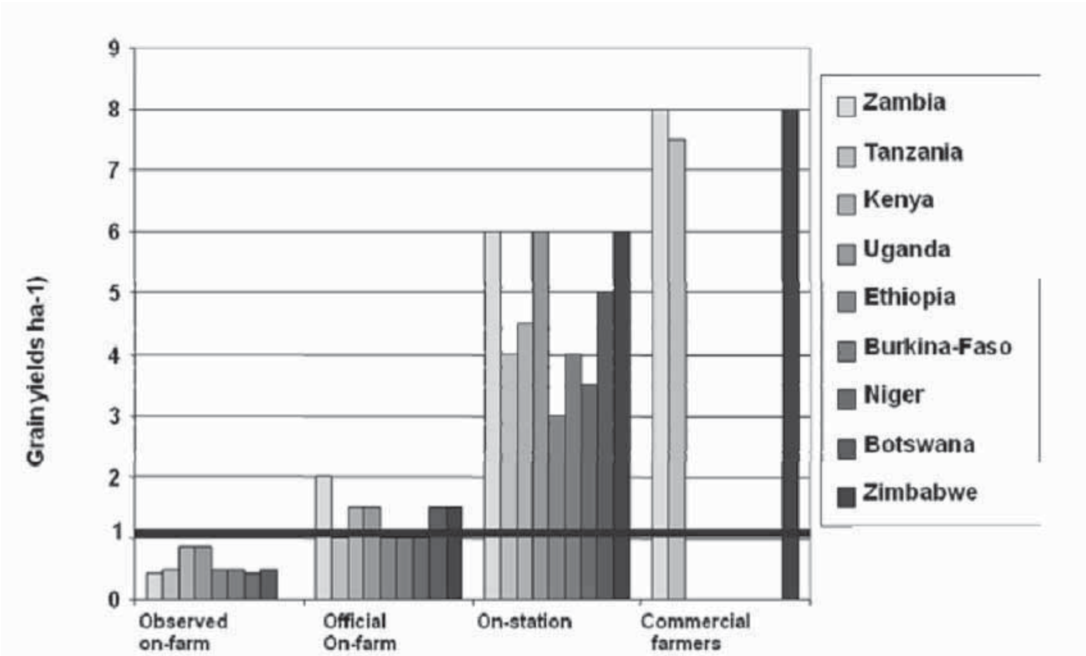



Figure 2.2. Reported maize grain levels in selected countries in sub-Saharan Africa indicating a substantial yield gap between on-farm, station and commercial activities (Bationo *et al.* 2006).

**ISFM guidelines for integrated fertilizer use**

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

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

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

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

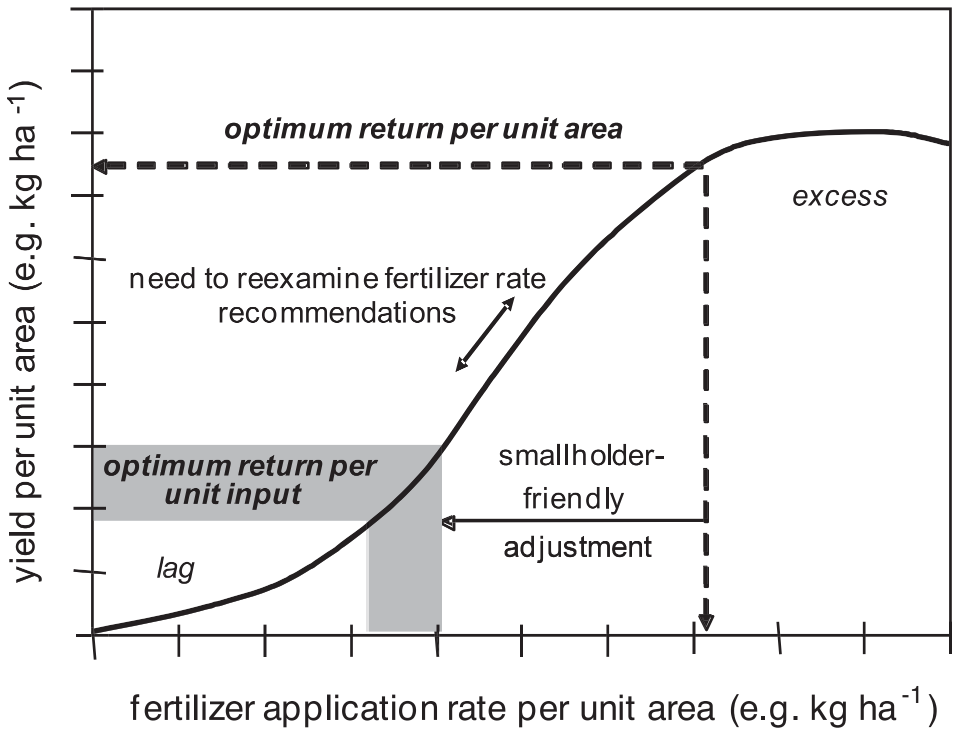



Figure 2.3. Fertilizer recommendations formulated for small-scale farmers should be based not upon maximizing return per unit area, as is customary, but rather optimizing return per unit fertilizer input.

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

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

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

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

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

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

# Chapter 3. Agro-minerals in ISFM

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

**Agro-minerals in Africa**

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

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

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

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

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

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

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

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

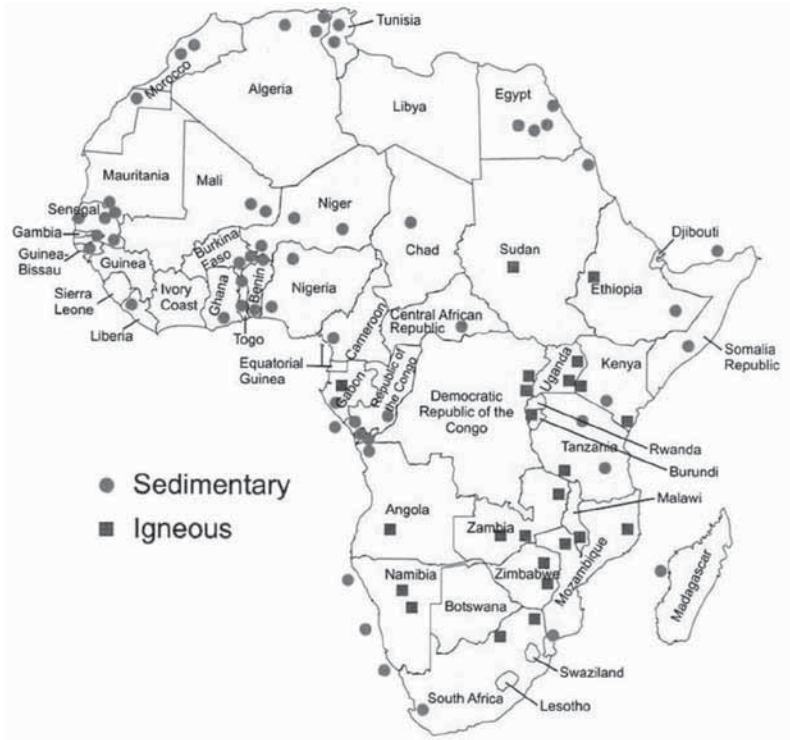



Figure 3.1. Sedimentary and igneous deposits of phosphate rock in Africa (after van Kauwenbergh, 2006)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

### Integrated use of agro-minerals

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

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

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

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

### Nutrient replenishment with agro-minerals

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

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

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

## Localized mining and processing

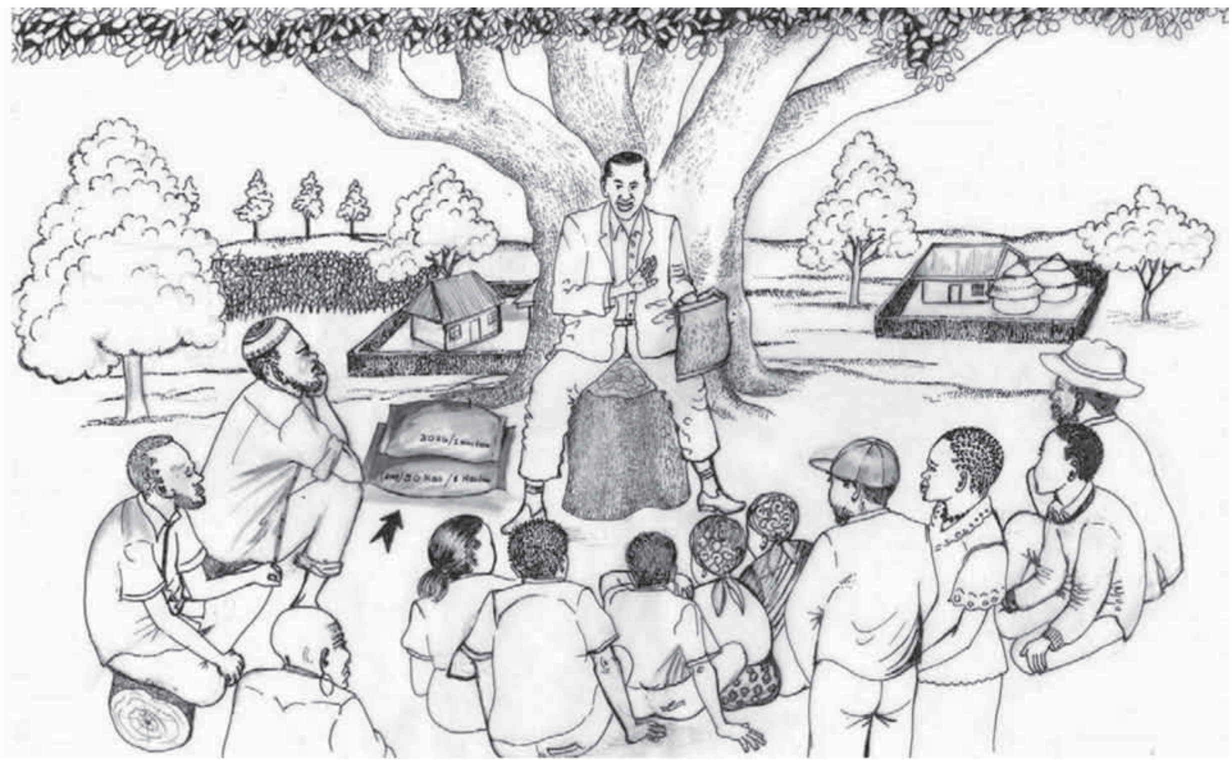
For sub-Saharan Africa to achieve targeted increases in fertilizer use and greater self-sufficiency in fertilizer production requires industrial scale exploitation of its largest agro-mineral deposits, but this does not preclude more localized efforts of mining and processing (Morris *et al.* 2007).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

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

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

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

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



# Chapter 4. Organic resource management

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

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

### Organic resource quality

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

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

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

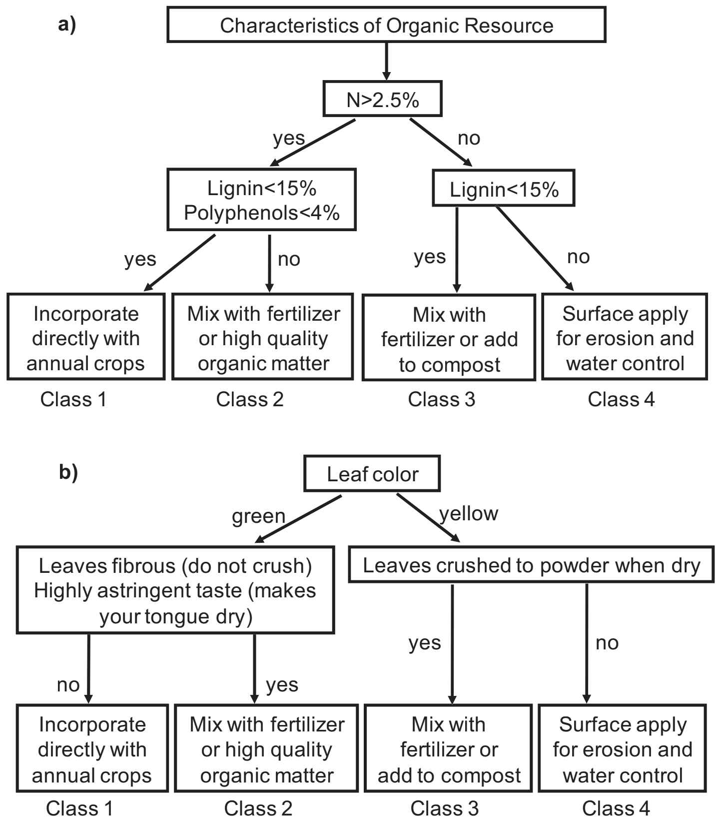


Figure 4.1 A decision tree to assist management of organic resources in agriculture. (a) is based on Palm *et al.* (2001); (b) is a farmer-friendly version of the same framework developed by Giller (2000).

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

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

**Farmer-available organic resources**

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

**Organic resource processing and application**

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

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

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

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

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

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

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

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

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

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

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

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

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

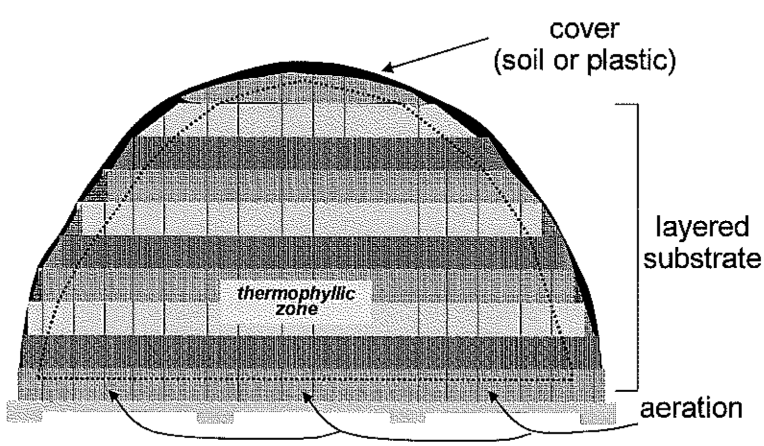



Figure 4.2. The principle elements of a compost pile including the interior thermophilic zone.

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

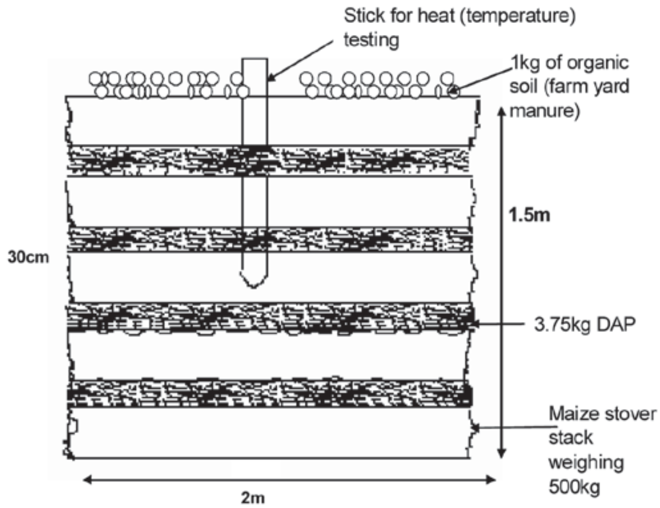



Figure 4.3. Producing fortified compost involves stacking different quality organic and mineral resources.

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

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

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

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

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

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

**Combined application of mineral fertilizer and organic resources**

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

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

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

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

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

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

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

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

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

## Improved nutrient use through local adoption of ISFM principles

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

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

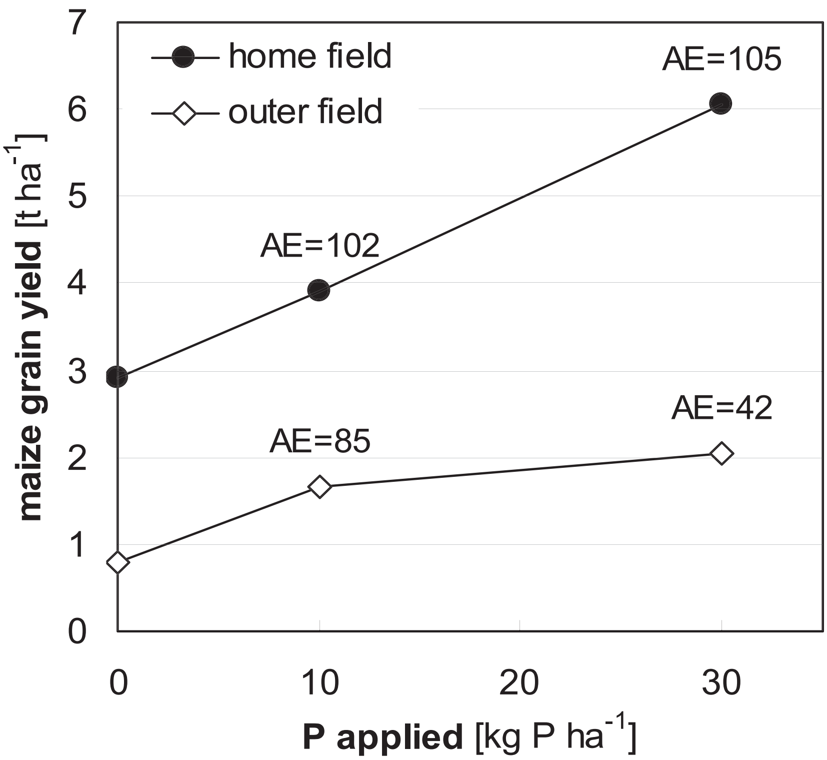



Figure 4.4. Maize response to SSP fertilizer application and AE in home and outer fields Murawe, Zimbabwe (Zingore *et al.* 2007b).

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

# Chapter 5. ISFM, soil biota and soil health

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

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

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

## Beneficial soil organisms

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

## Soil biological processes and land management

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

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

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

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

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

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

**Introduction of beneficial organisms**

**Inoculation with rhizobia.** The first patents on rhizobial inoculation were filed at the end of the 19th Century shortly after the recognition that legume root nodules were the site of BNF by symbiotic bacteria, rather than pathological galls. Thus the concept of manipulating BNF by the introduction of strains of bacteria goes back almost 120 years (Eaglesham 1989). The three main producers of soybean, which also produce the largest amounts of rhizobial inoculants are USA, Brazil and Argentina (Saint Macary *et al.* 1993). Similarly, most of the inoculants produced in other countries are for use with soybean as the coverage of this crop expands. The soybean varieties that are cultivated by commercial farmers are specific in their nodulation requirements and compatible rhizobia are rarely present. In Australia, inoculants are also commonly applied to crop and pasture

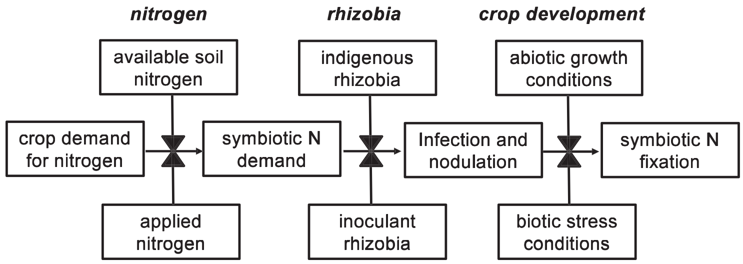



Figure 5.1. Factors regulating legume BNF may be used to predict where and when successful symbiosis will be established.

legumes because most of these legumes were introduced from other continents and indigenous rhizobia are absent, host incompatible or weakly symbiotic (Howieson *et al.* 2000; O'Hara *et al.* 2002). A similar trend in rhizobial population sizes was noted in the drier cultivated areas of East and Southern Africa (Woomer *et al.* 1997).

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

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

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

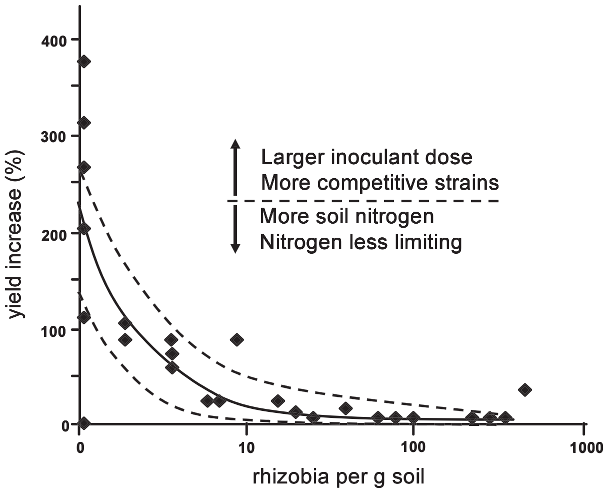



Figure 5.2. The population size of indigenous rhizobia affect observed inoculation response.

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

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

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

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

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

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

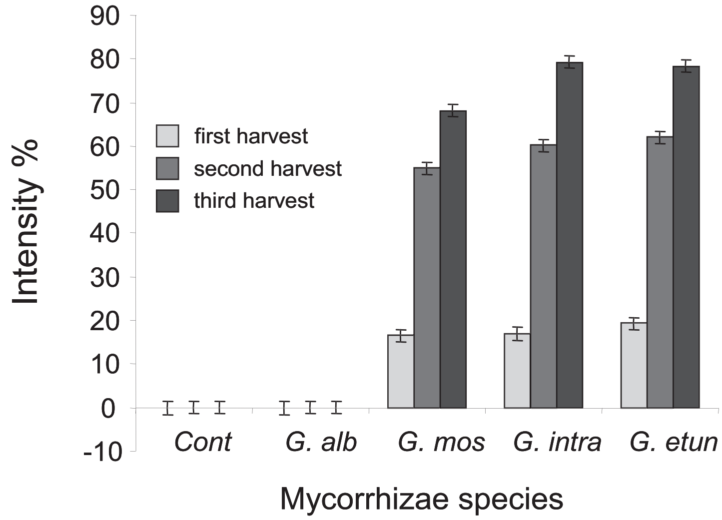



Figure 5.3. Infection intensity for banana after 8, 18 and 22 weeks following inoculation with four species of mycorrhizae (Jefwa, 2005. TSBF report to the Rockefeller, unpublished).

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

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

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

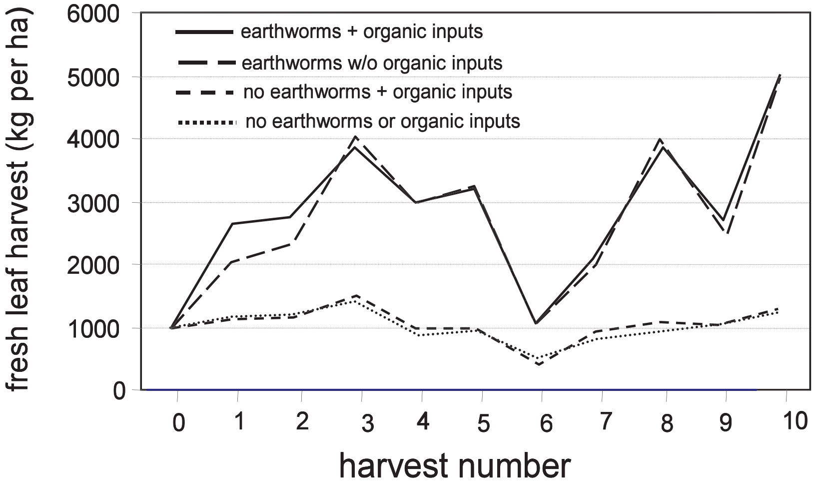



Figure 5.4. Monthly green leaf tea production following introduction of earthworms and organic inputs at the Sheikamuli Tea Estate, Tamil Nadu, India (after Lavelle 1996).

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

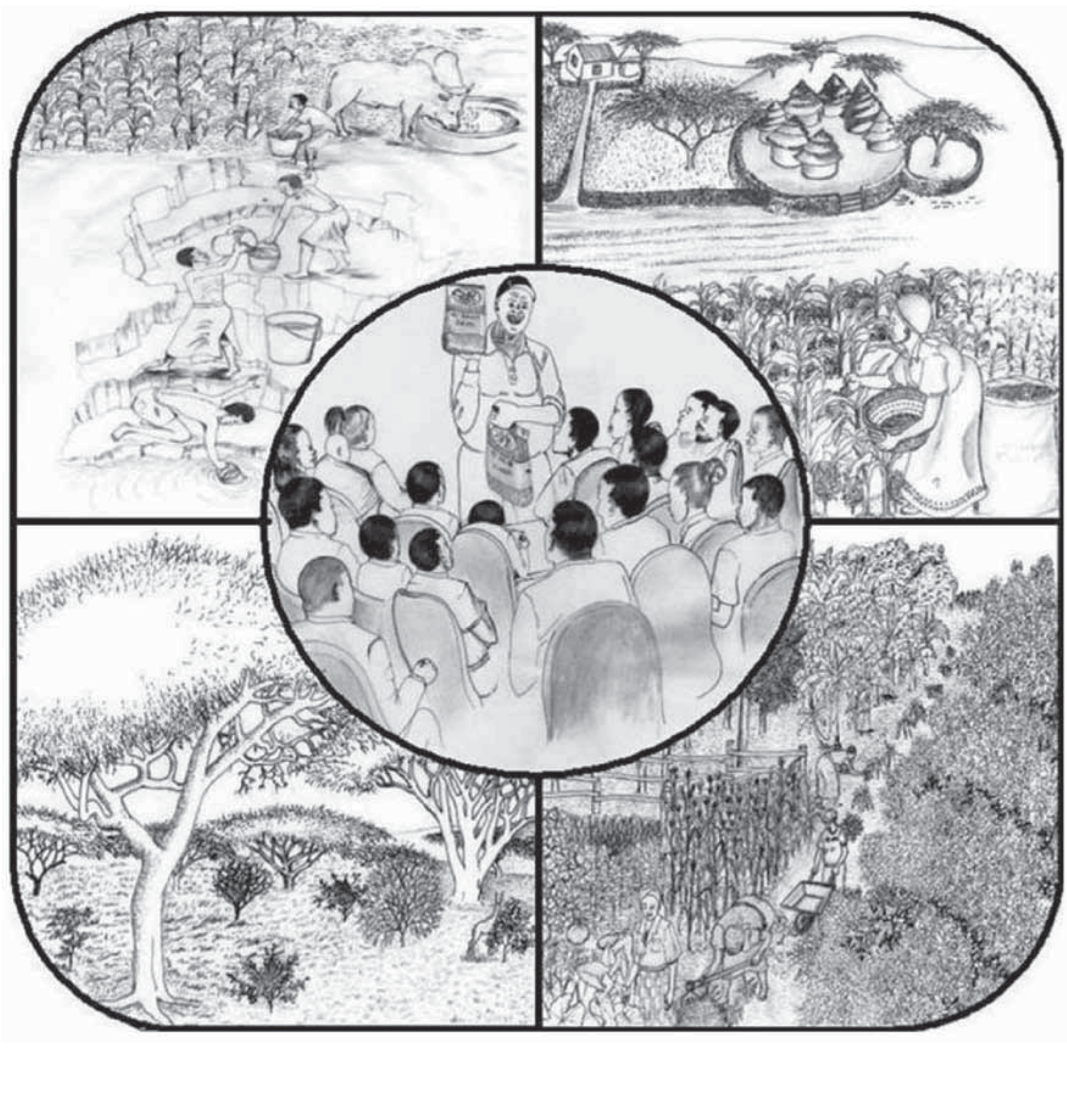
Another successful introduction of macrofauna involves millipedes in Kenya. Bamburi Cement Limited began operations near Mombasa in 1954, mining a fossilized coral reef as raw material in quarries that later extended for 6 km. Excavation for the coral limestone extended to just above the saline groundwater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

**Conclusion**

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

# 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$^{-1}$) | 2004: production costs: total (KSh ha$^{-1}$) | 2004: net return (KSh ha$^{-1}$) | 2004: benefit: cost ratio | 2008 costs and prices: production costs: fertilizer (KSh ha$^{-1}$) | 2008: production costs: Total (KSh ha$^{-1}$) | 2008: net return (KSh ha$^{-1}$) | 2008: 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

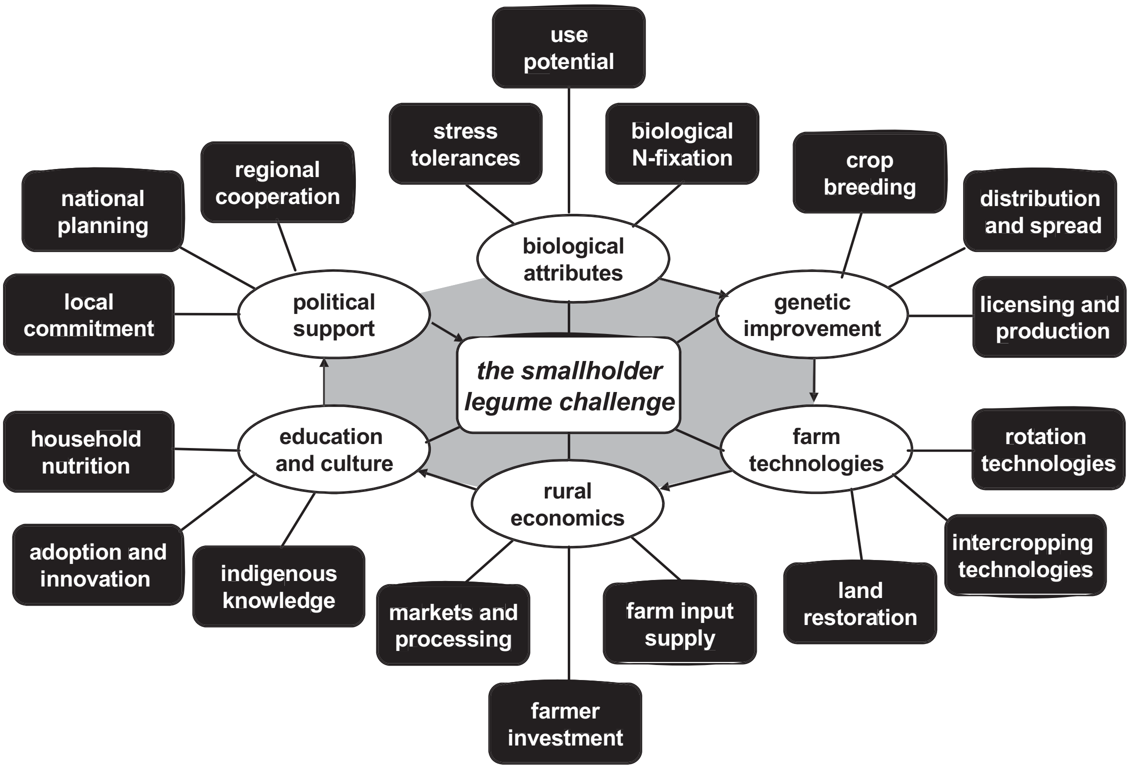



Figure 6.1. The challenge of increasing legume enterprises within small-scale farms in Africa has several key aspects relating to biology, crop genetic improvement, useful technologies, rural economic, cultural perspectives and political support.

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

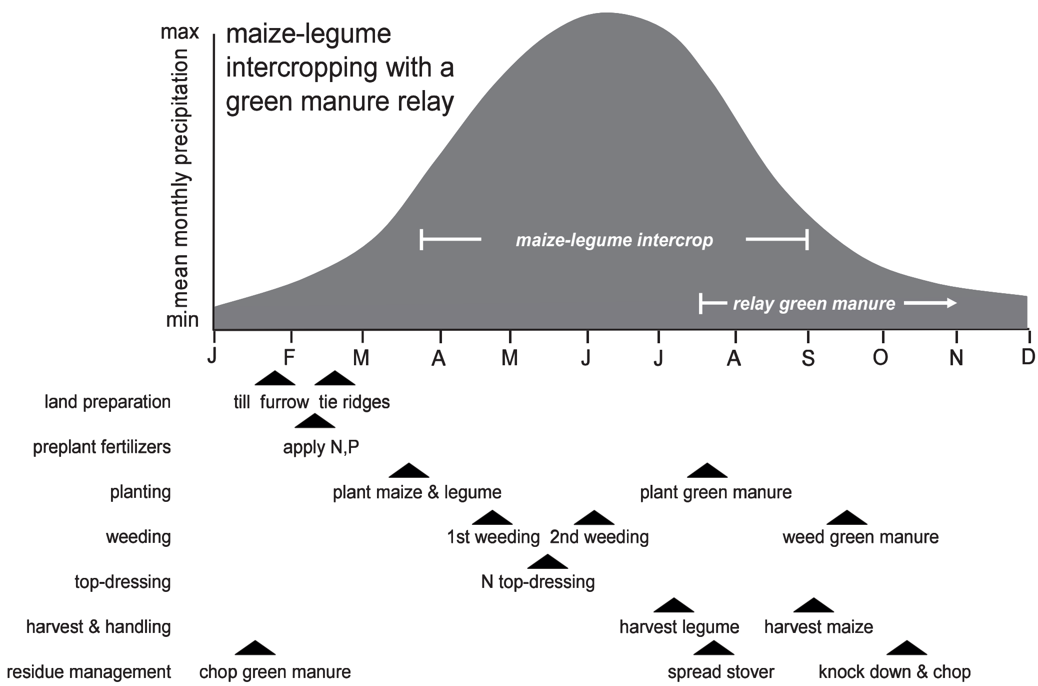



Figure 6.2. An ISFM management scenario suitable for cereal and grain legume production within a semi-humid, monomodal rainfall regime

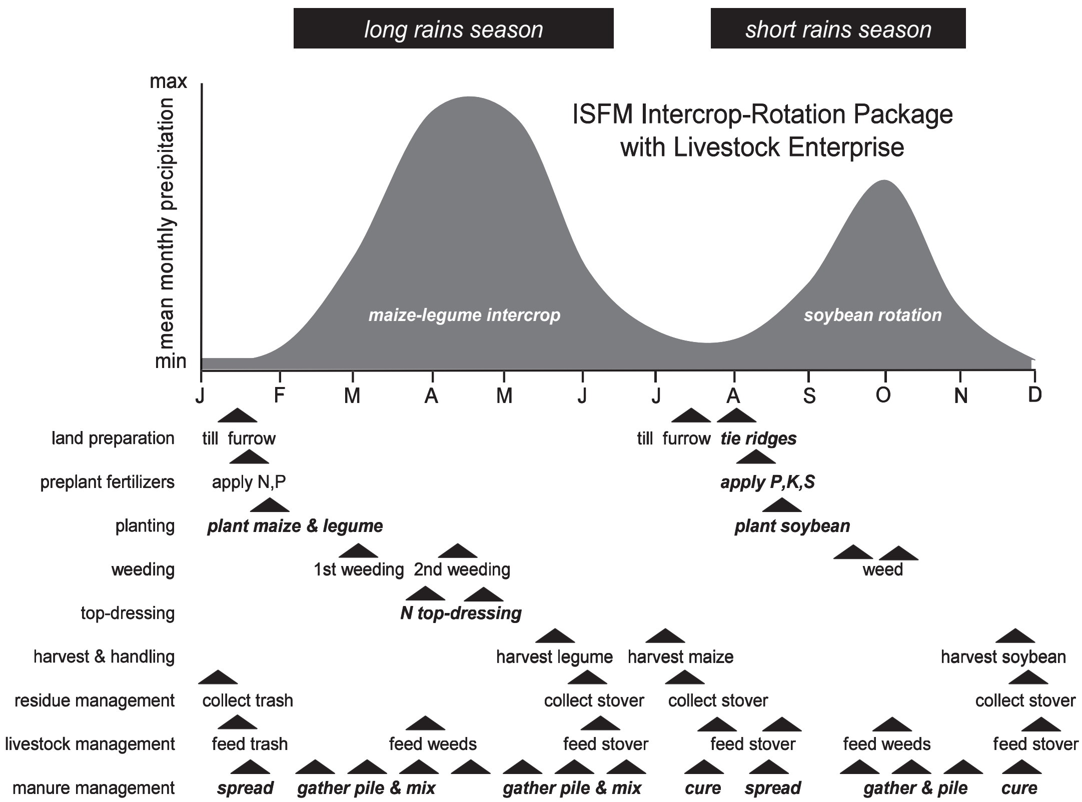



Figure 6.3. An ISFM package designed for cereal-legume cropping and livestock enterprise in a sub-humid climate with a pronounced bimodal precipitation pattern.

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

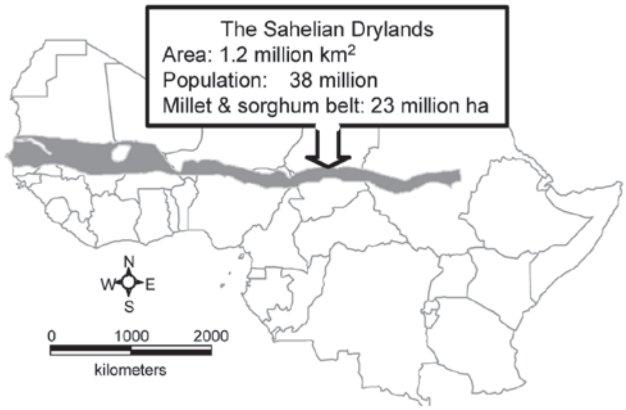



Figure 7.1. The Sahelian Drylands is an agricultural belt vulnerable to drought that stretches between Senegal and Sudan.

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) |

**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).

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 |

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.

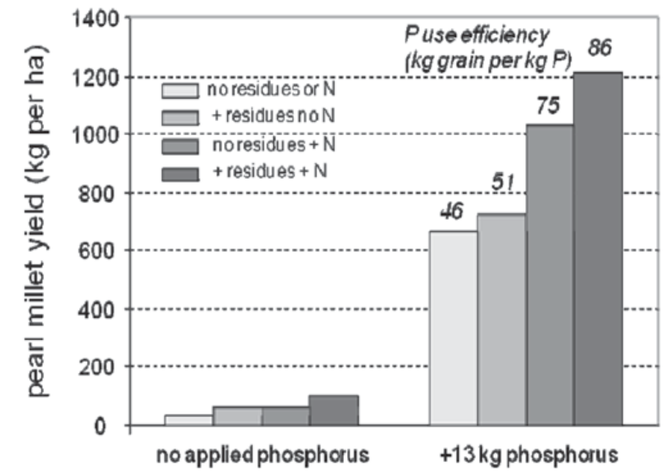



Figure 7.2. Effect of fertilizer and crop residue on pearl millet yield in Sadore, Niger (after Bationo 2008).

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).

**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.

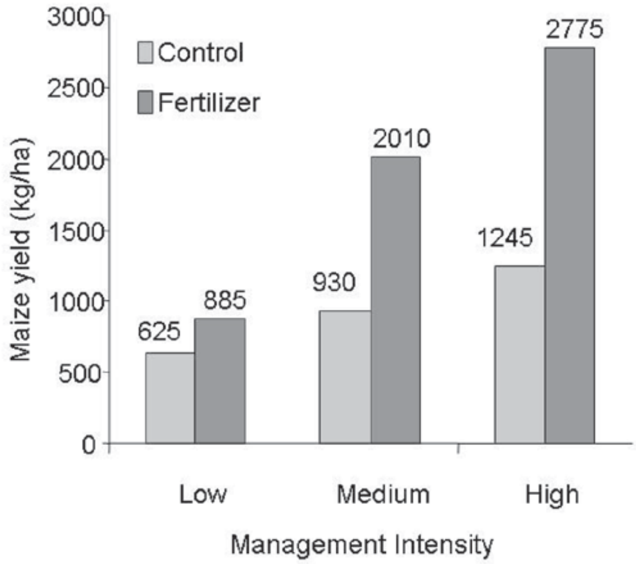



Figure 7.3. The effect of management intensity (planting date, crop density and time of phosphorus application) on maize grain yield at Tinfouga, Mali (Bationo *et al.* 1997).

**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

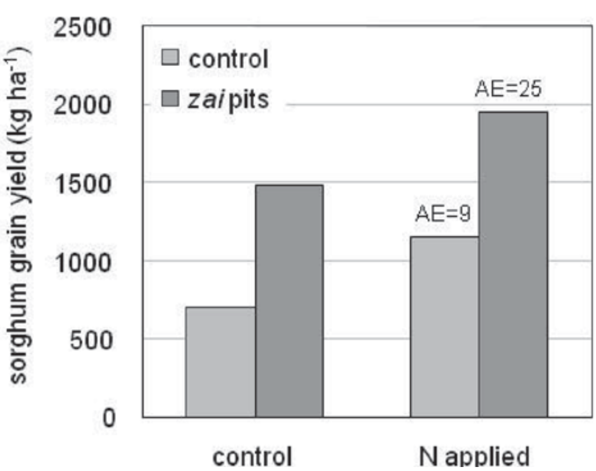



Figure 7.4. Sorghum yields obtained using *Zai* pits and urea application at 50 kg N $ha^{-1}$ at Tougouri, Burkina Faso (A. Bationo, personal communication)

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

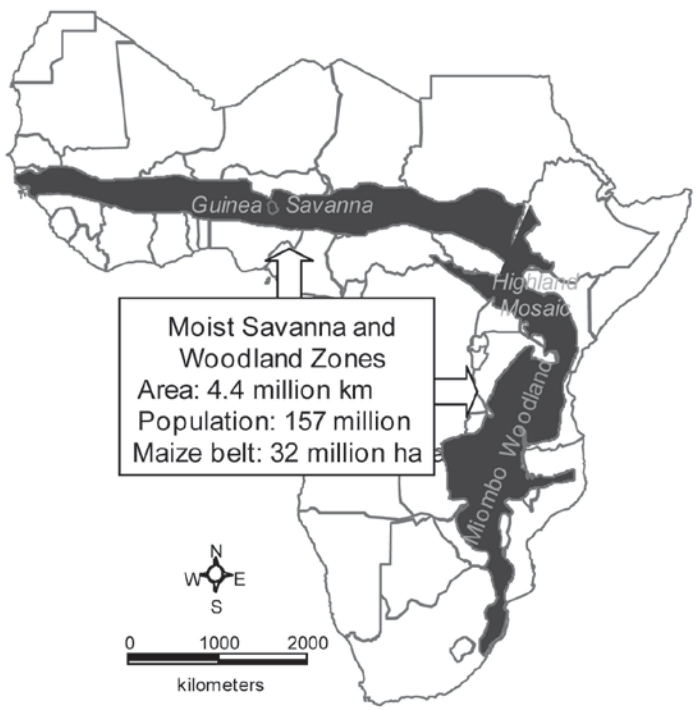



Figure 8.1. Coverage of the moist savanna and woodland zone that is suitable to maize-legume cropping includes the Guinea Savanna of West Africa, the Miombo Woodlands of Southern Africa and East Africa's Highland Mosaic.

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).

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 |

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).

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

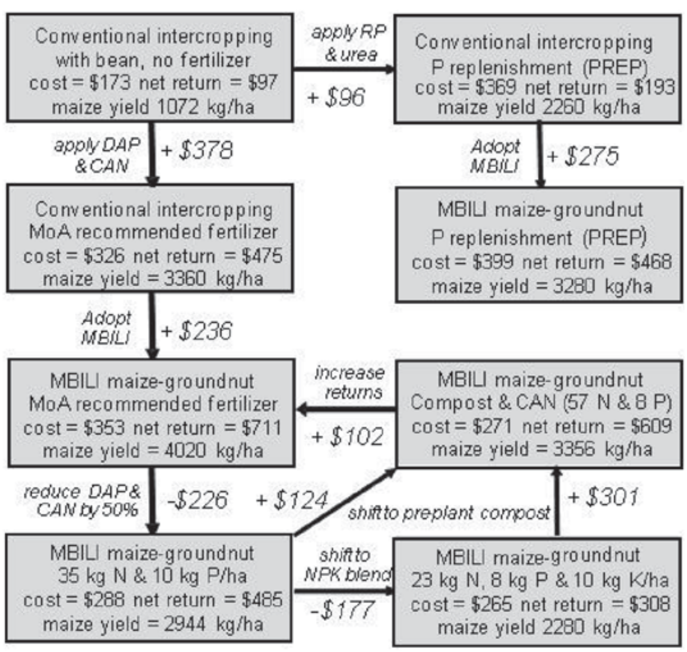



Figure 8.2. Soil fertility management options examined in Vihiga, Kenya during the 2004 long rains. MBILI is a locally developed maize-legume intercropping arrangement with paired, staggered rows.

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

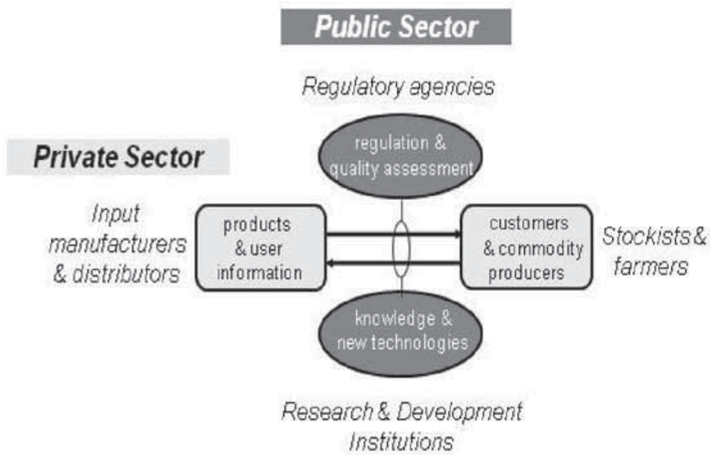



Figure 8.3. Public-private partnership is necessary to provide quality ISFM products to small-scale farmers.

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 |

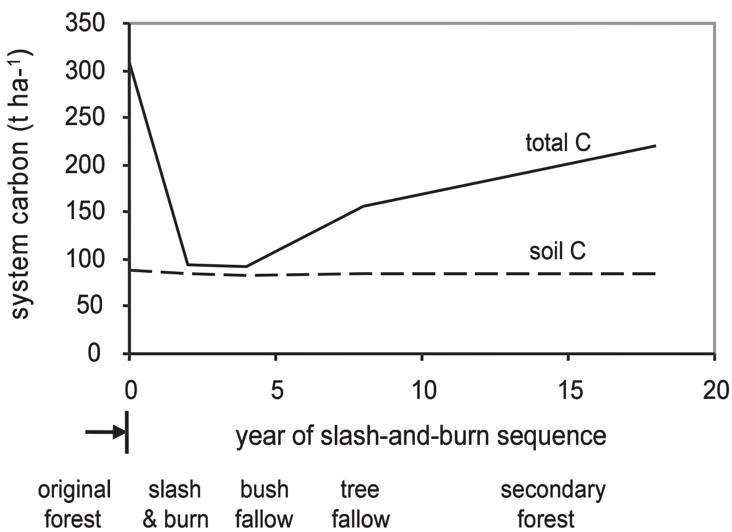



Figure 9.2. Carbon dynamics in slash-and-burn systems in southern Cameroon (after Kotto-Same *et al.* 1997).

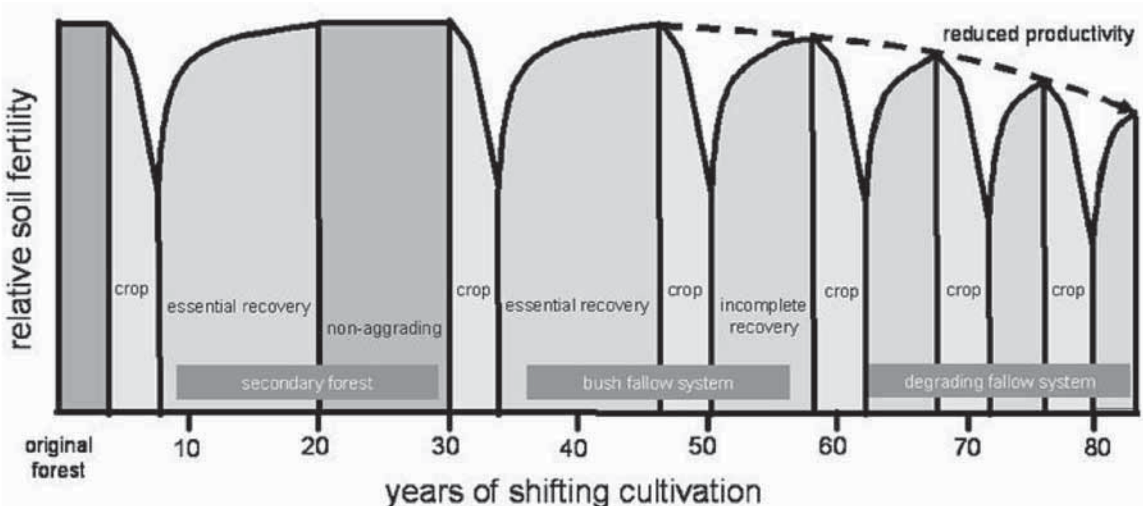



Figure 9.3. Hypothetical relationship between fallow interval, soil fertility renewal and system productivity as land use changes from slash-and-burn to bush fallow and degrading bush fallow systems (after Hauser *et al*. 2006).

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).

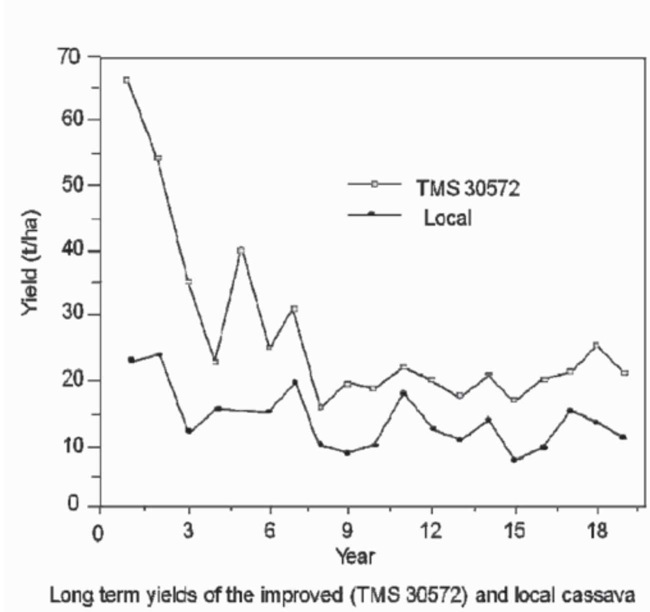


Figure 9.5. Long term yield performance by an improved cassava variety (TMS 30572).

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

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 |

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).

**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

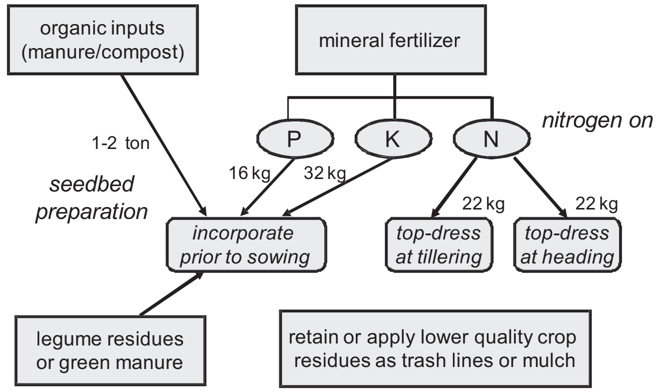



Figure 9.6. An ISFM strategy applied to upland rice (after Jacquot and Courtois 1987)

(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.

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 | Recommended addition | | |
|---|---|---|---|---|
| | t $ha^{-1}$ | 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

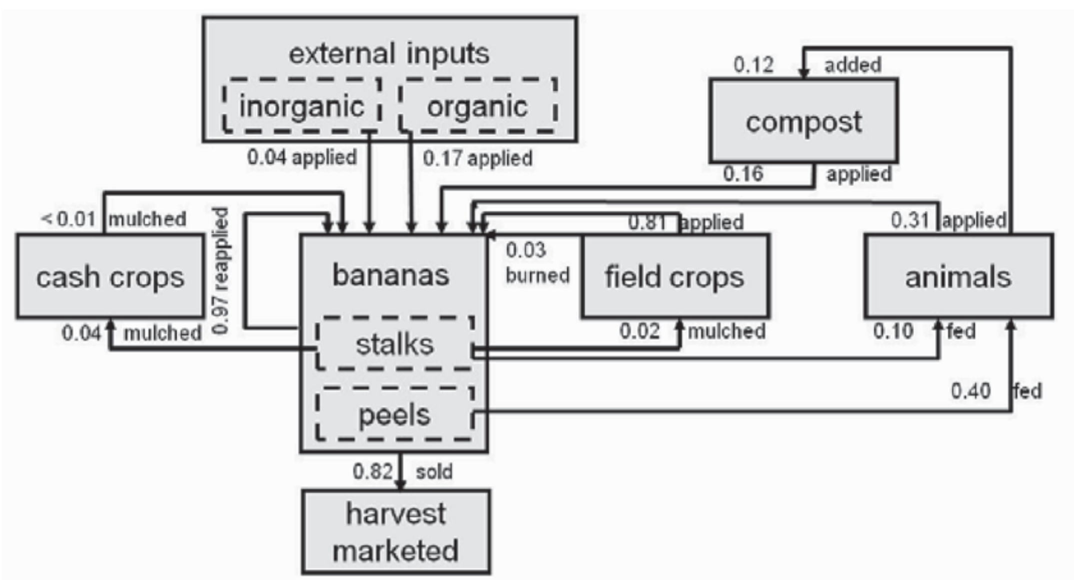



Figure 9.7. Frequency of input application and transfer in banana-based cropping systems of Uganda (after Bekunda and Woomer 1996).

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.

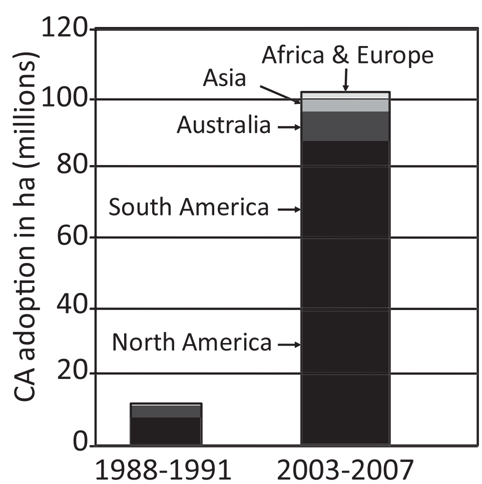



Figure 10.1. Increase in the coverage of Conservation Agriculture in different areas of the world (after FAO 2008).

### 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).

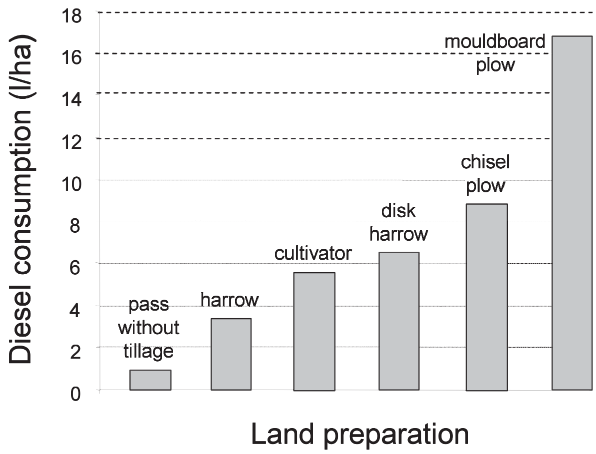



Figure 10.2. Diesel fuel consumption while performing different tractor operations (after Nalewaja 2001).

**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

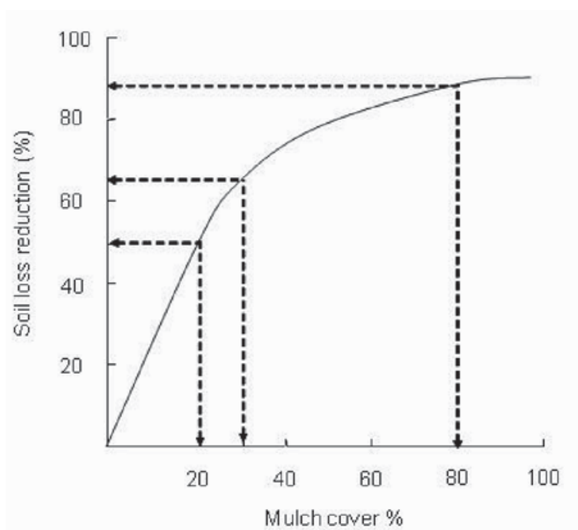



Figure 10.3. The relationship between mulch cover and loss to soil erosion.

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-

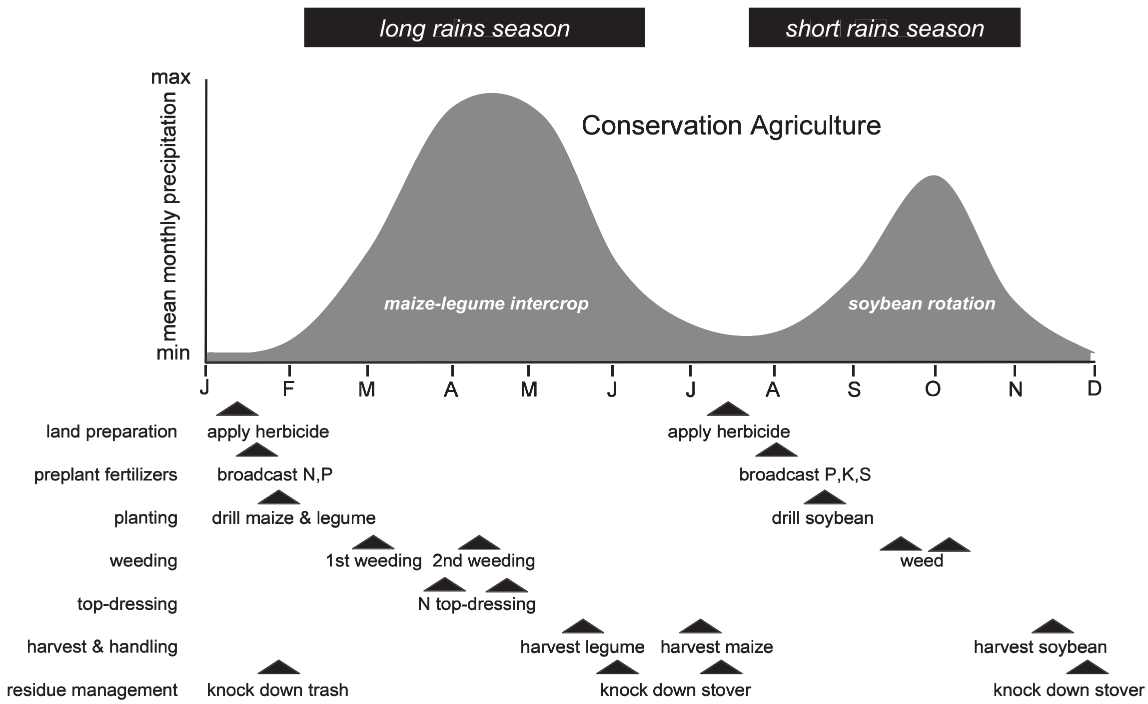



Figure 10.4. ISFM practice within the context of Conservation Agriculture in a sub-humid bimodal rainfall regime.

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.

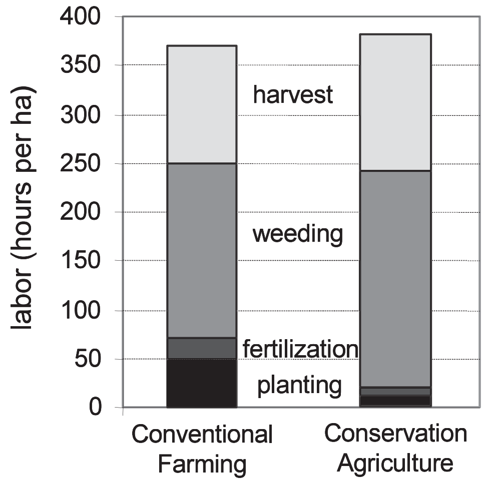


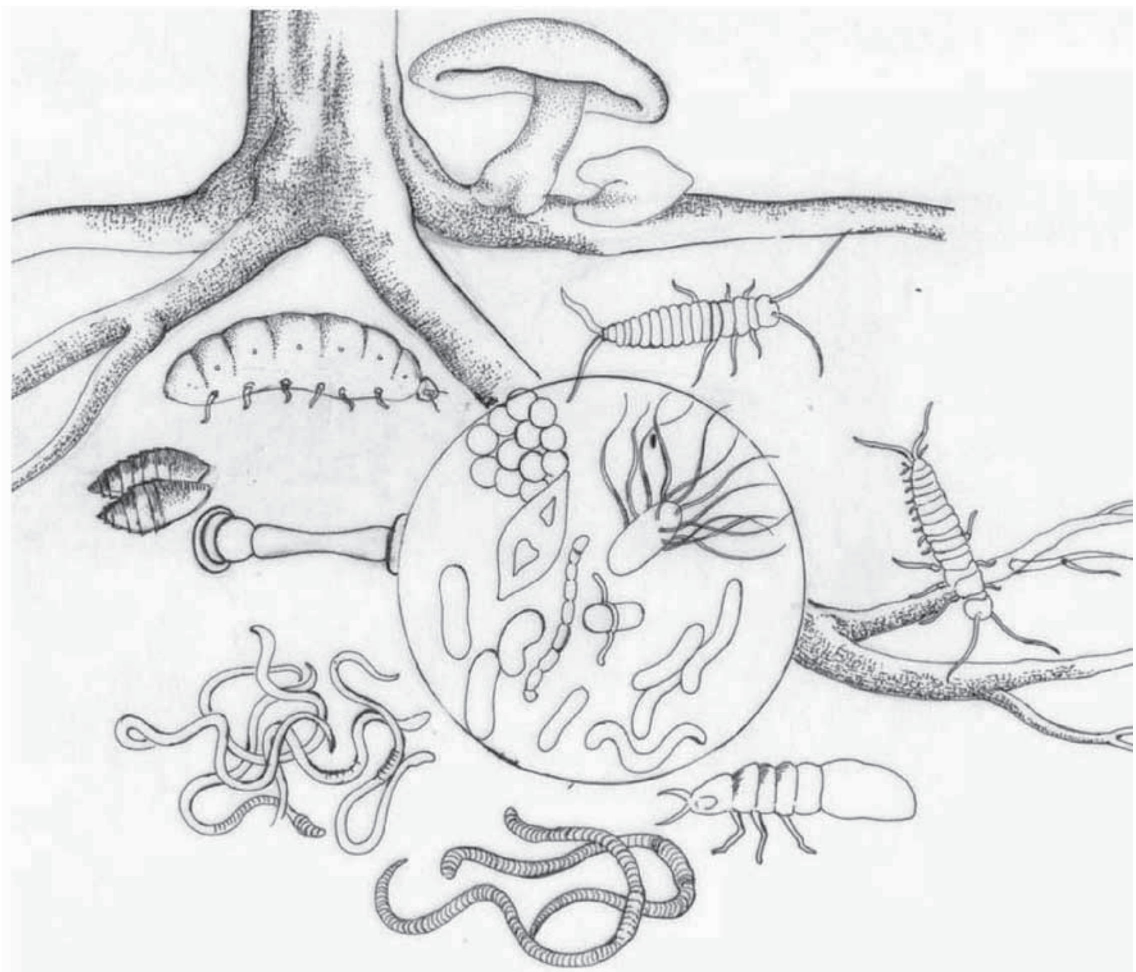

Figure 10.5. Labor requirements of conventional farming and conservation agriculture from an experimental site in Zimbabwe (after Siziba 2008).

### 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.

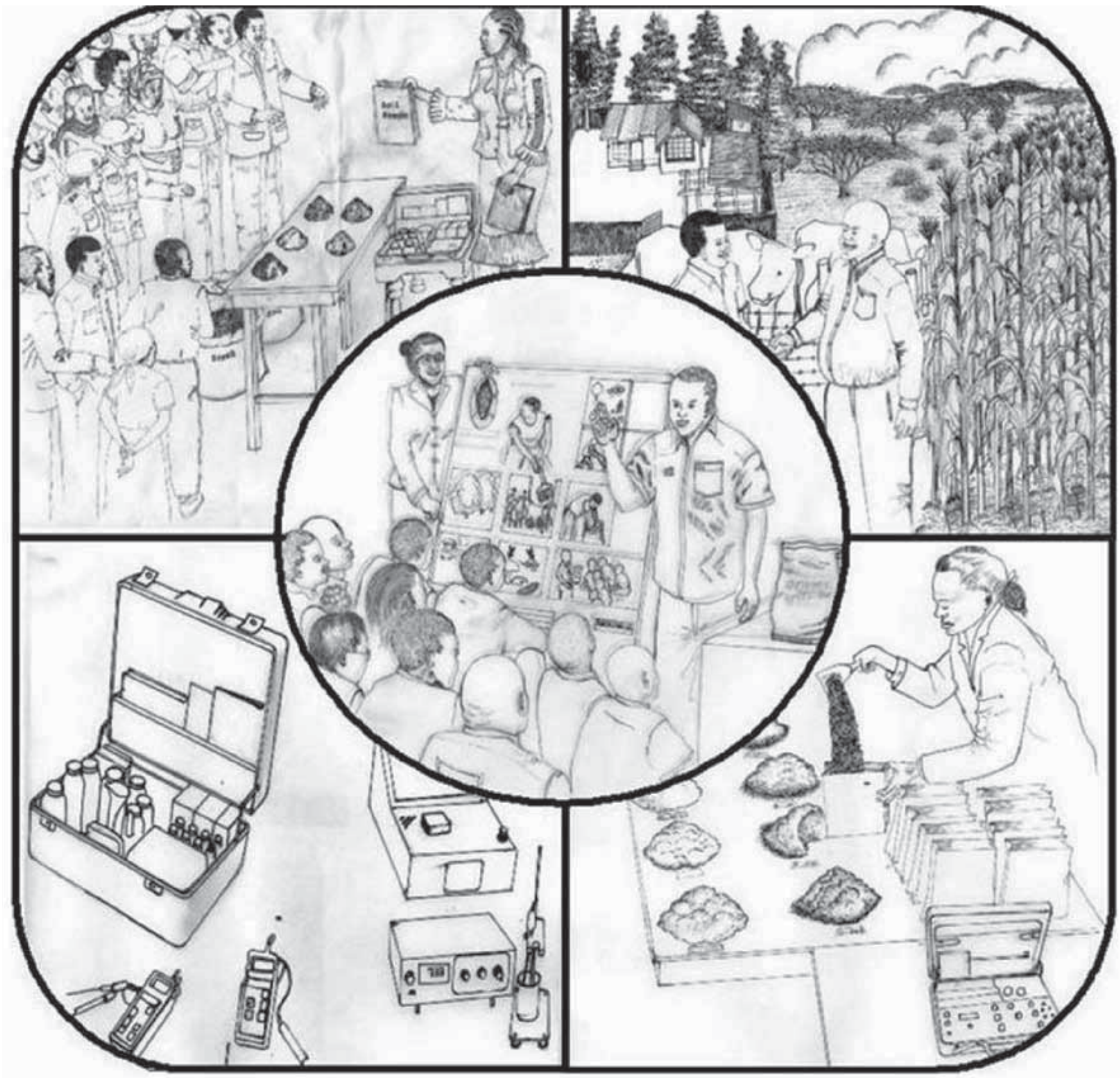
The constraints to adoption of Conservation Farming by small-scale farmers may in fact be more fundamental than just competition for crop residues. Conservation Agriculture requires long-term planning and a commitment to agricultural resource protection. A new suite of skills are required in fertilizer 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.



# Part III

# The Process of Implementing ISFM



# Chapter 11. Soil fertility diagnosis

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

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

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

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

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

## Plant nutrients, their deficiency symptoms and amelioration

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

## Diagnostic Approaches

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

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

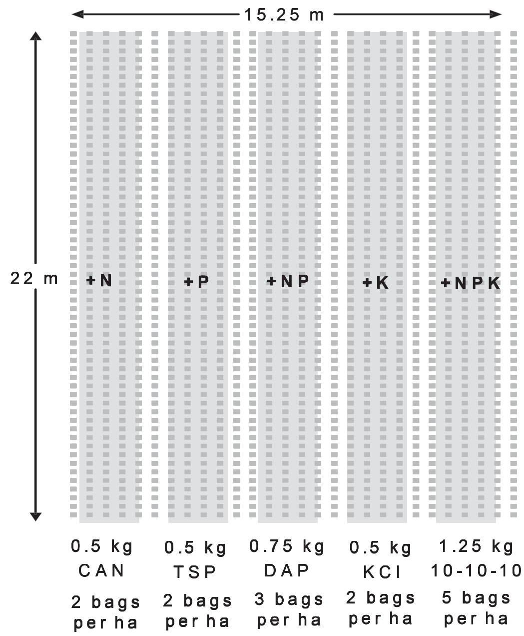



Figure 11.1. An example of fertilizer test strips installed at a moderate fertility level intended for on-farm diagnosis of fertilizer requirements. Each strip is equivalent to 0.005 ha containing 300 maize plants in four 75 cm rows.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Fertilizer guidelines resulting from soil tests may be adjusted by other factors that account for:
1. nutrient supply from beyond the soil sample
2. nutrients recycled from organic sources
3. nutrients resulting from deposition, weathering, nitrogen fixation and contaminants in mineral fertilizers
4. difference is nutrient use efficiency by different crops and for different nutrients

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

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

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

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

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

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

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

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

## Integrating diagnostic approaches

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

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

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

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

# Chapter 12. Soil fertility management advice

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

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

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

**Examples from Africa**

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

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

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

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

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

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

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

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

### Fertilizer rates and blends

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

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

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

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

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

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

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

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

### Perceptions of management recommendations

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

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

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

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

**ISFM-based advice**

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

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

# Chapter 13. Dissemination of ISFM technologies

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

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

### Reaching farmers with target recommendations

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

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

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

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

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

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

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

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

**Enabling farmers as ISFM practitioners.**

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

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

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

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

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

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

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

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

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

# Chapter 14. Designing an ISFM adoption project

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

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

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

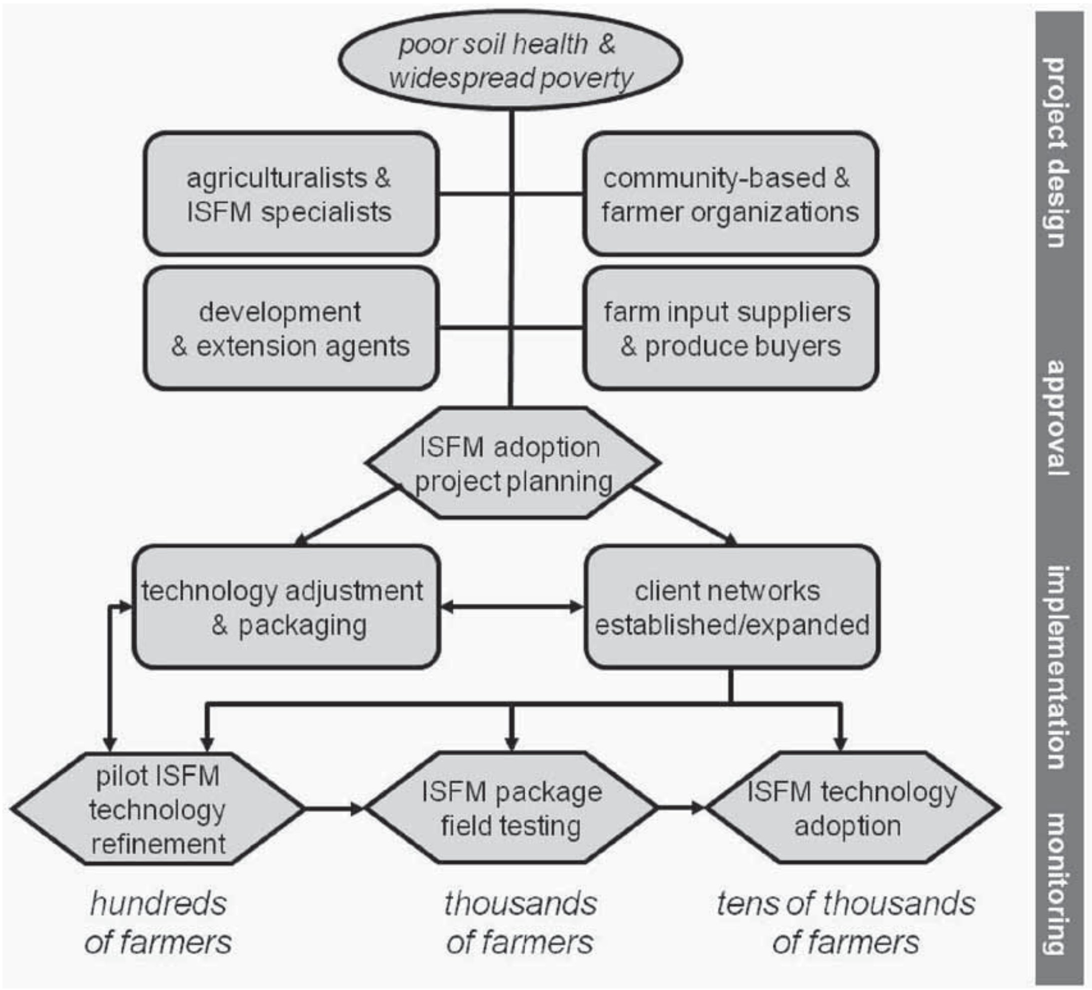



Figure 14.1. The design and operations of an innovative ISFM adoption project based upon proven, packaged technologies channeled to farmer organizations through the private sector.

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

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

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

**Examples of ISFM packages.**

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

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

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

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

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

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

**Improving Linkage to Markets**

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

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

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

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

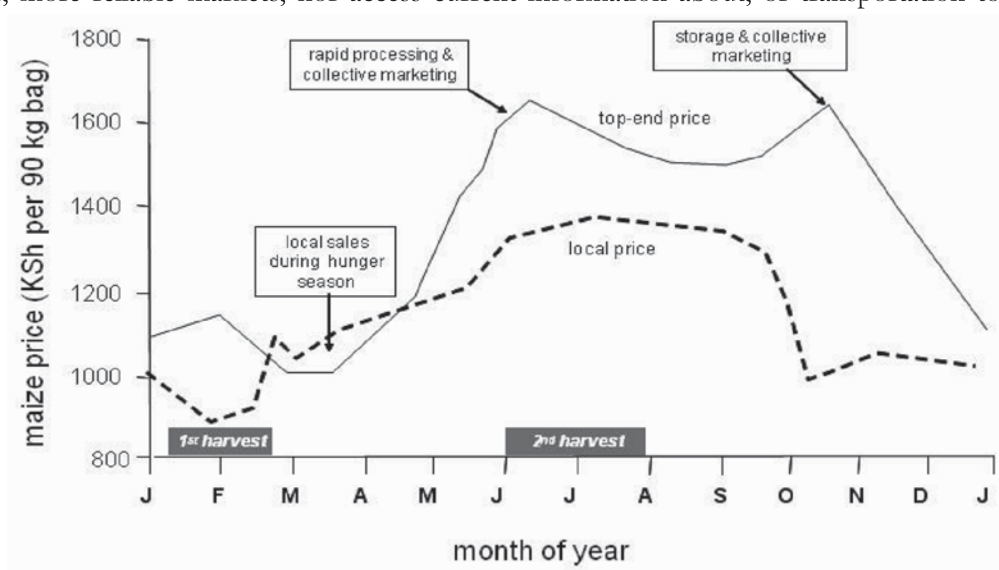



Figure 14.2. Price trends and marketings strategies for maize in west Kenya, an area with bimodal rainfall.

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

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

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

**Projecting Impacts**

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

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

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

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

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

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

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

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

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

**Summarizing an ISFM adoption project**

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

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

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

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

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

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

**Monitoring soil health**

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

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

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

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

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

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

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

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

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

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

***Legume root nodulation.*** The presence and effectiveness of rhizobia, the microsymbiont associated with nitrogen-fixing legumes, may be inferred by the abundance, size and interior coloration of root nodules. No nodules imply that the host's specialized rhizobia are absent. Sporadic, small nodules with white interiors suggest that infective rhizobia are present but are not symbiotically active. Legumes require inoculation when soil rhizobia are absent or ineffective. Abundant, large nodules with red interiors indicate that the soil rhizobial population is healthy, at least for that specific legume. In general, legumes nodulated by the so-called cowpea miscellany (*Bradyrhizobium sp.*) find symbiotic partners in most soils, but they do not necessarily enter into vigorous N-fixing relationships with them. Over time, however, legumes enrich their soil environment with effective rhizobia. A key to ISFM is to promote BNF so that its products result in acceptable legume yields and offer residual benefits to following crops. Legume nodules may be scored as absent (0), sporatic (1), abundant (2) and, as occasionally observed, super-abundant (3) and their interiors may be rated as white (0), pink (1), red (2) and dark red (3). Experience is required in this evaluation because legumes have typically different nodule shapes and sizes and, as effective nodules age their interior colour changes.

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

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

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

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

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

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

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

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

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

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

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

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

# Chapter 15. ISFM at farm and landscape scales

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

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

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

### Preventing land degradation

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

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

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

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

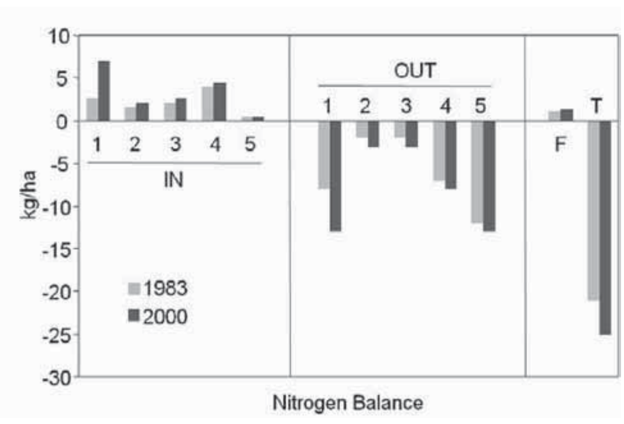



Figure 15.1. Nitrogen balance in Sub-Saharan Africa (Stoorvogel *et al.* 1993). Inputs (IN) 1=Mineral fertilizer, 2=Organic inputs, 3=atmospheric deposition, 4=biological N fixation, 5=sedimentation. Outputs (OUT) 1=harvest products, 2=crop residue residual, 3=leaching, 4=gaseous loss, 5=runoff and erosion.

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

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

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

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

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

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

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

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

## Diversity in agro-ecological and socio-economic conditions

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

## Targeting technologies

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

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

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

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

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

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

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

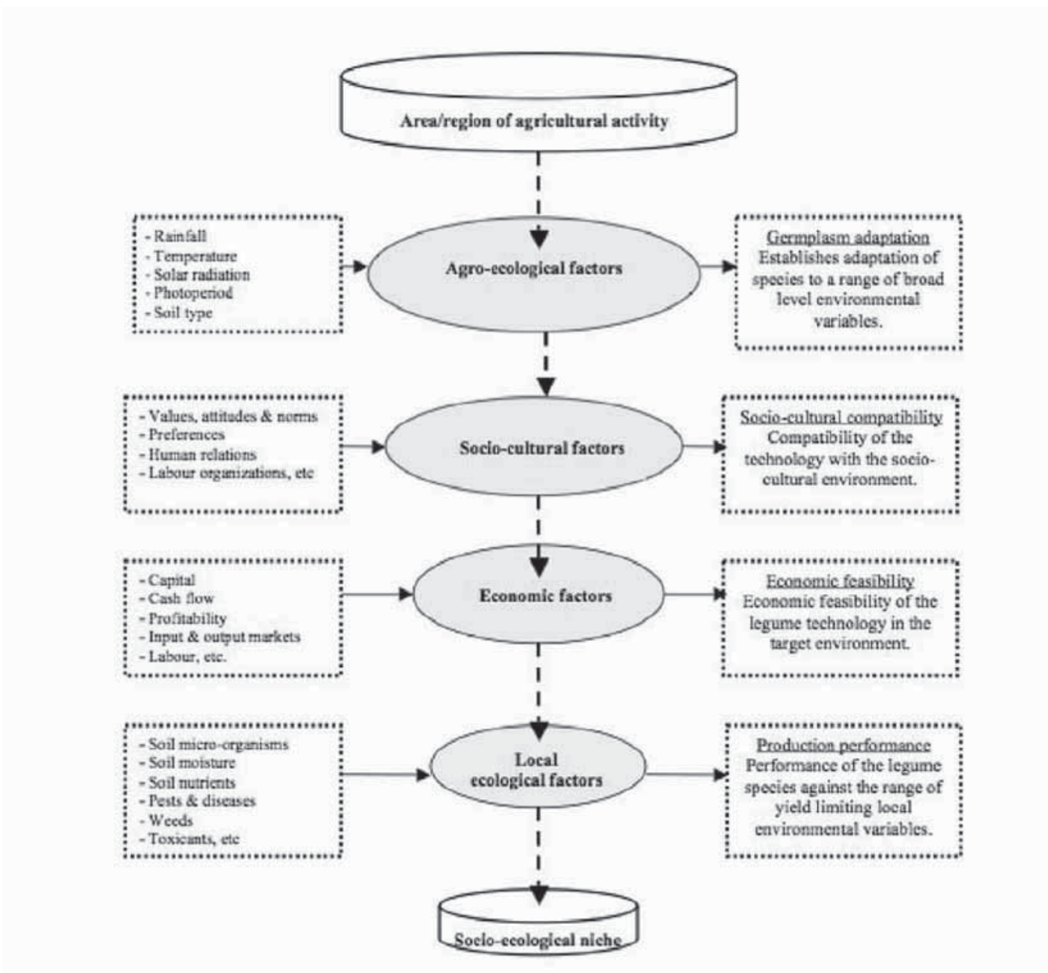



Figure 15.2. The socioecological niche is described by a combination of agroecological and socioeconomic factors (from Ojiem *et al.* 2006).

**Evidence-based diagnostic surveillance of soil degradation.**

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

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

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

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

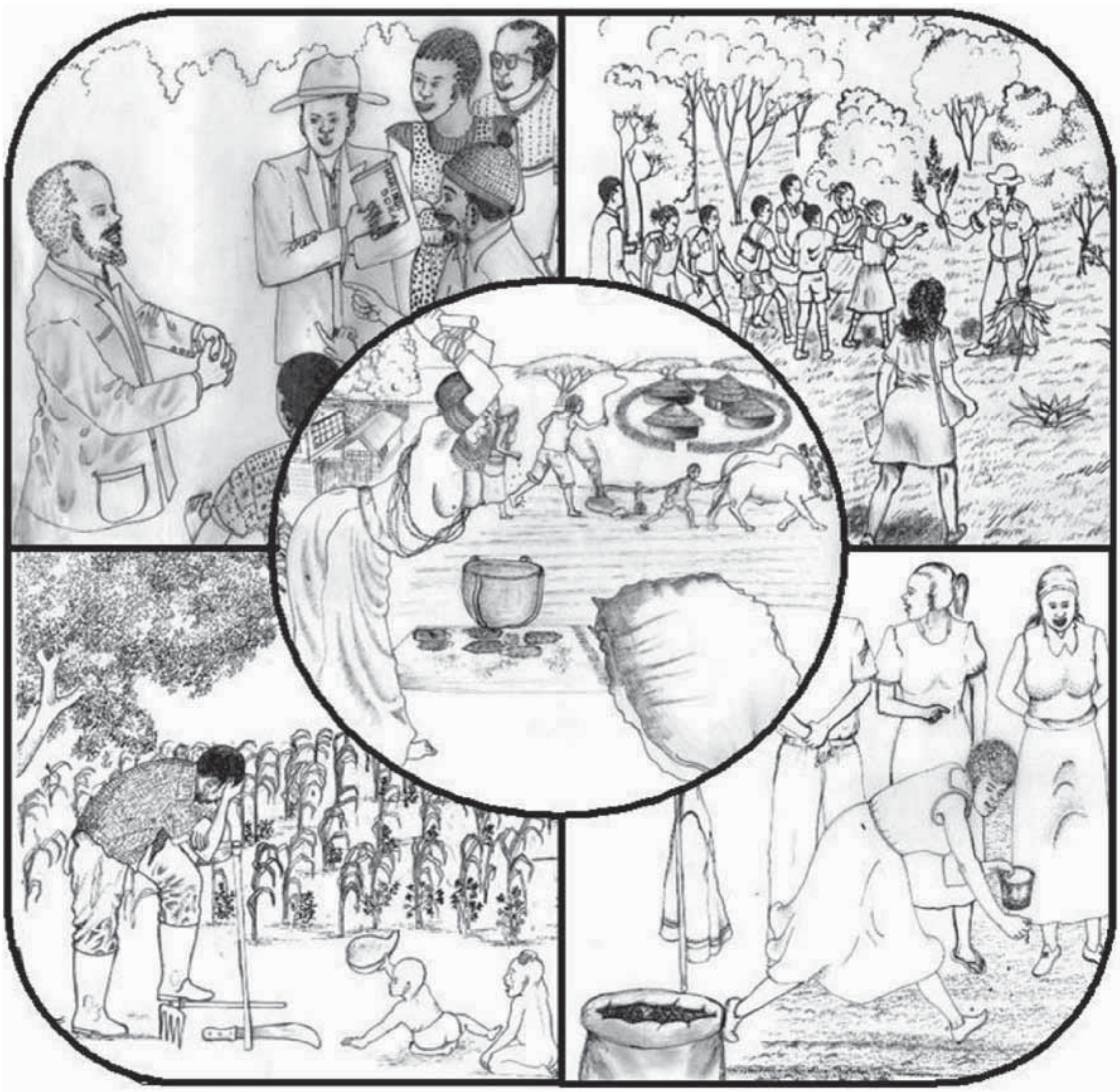
(Shepherd and Walsh 2007). This non-chemical approach requires little sample preparation and covers many applications with the same instrument, having obvious advantages for developing countries. Low cost and high-throughput methods make large-scale area diagnostic surveys more feasible.

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

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

# Part IV

## The Social Dimensions of ISFM



# Chapter 16. The role of ISFM in gender empowerment

ISFM practice by small-scale farmers in Africa necessarily involves all members of the household. Soil management is an essential farming task that should not further contribute to the drudgery of subsistence agriculture but rather reduce work burdens through efficiency and the substitution of skills and technologies for unnecessary labor operations. Small-scale farming households are subject to human resource traps where exhausting labor produces too little and illness and poor nutrition further reduce labor availability. Many farming practices are necessarily energy intensive, particularly land preparation that can test the endurance of family members. Small-scale farmers locked into high energy-low return farming are not well positioned to increase their workload but ISFM practices often allow for tasks to become more diversified as it involves new skills, technologies and investment, offering higher returns to labor. These benefits are readily passed to family members, including the elderly, women and children, through reduced workloads, improved farm ergonomics and occupational safety (Jafry 2000).

Decades of studies have described how African women conduct a large proportion of agricultural tasks while being disadvantaged in terms of access to information, land, cash and credit (Gladwin *et al.* 1997). Women are not only hindered by unequal opportunities within their families and communities, but many development programs tend to be male-oriented and consequently fail to recognize the special roles and potentials of women farmers (Burton and White 1984; Staudt 1975). Despite women providing 46% of farm labor and producing up to 80% of the household food supply, social scientists during the 1970s and 1980s too seldom collected gender-specific information, contributing to the failure of rural development specialists to build effective assistance programs around them.

Approaches to link farmers to markets that do not account gender in terms of access and outcomes are likely to compound existing inequalities. Women in Africa face several constraints as they endeavor to engage with market systems. Social and cultural customs that assign home and reproductive roles to women limit their commercial potential (OECD 2006). Women's agricultural activities in Africa are frequently oriented towards subsistence production and local markets producing reduced value crops on smaller tracks of land and have lower access to capital and inputs (Quisumbing 1996). Gender related barriers to markets create income disparities with men receiving higher income from market linkages. Women face mobility constraints that restrict their ability to travel or sell in more distant markets offering higher prices. Women receive lower prices for their produce because they sell in smaller volumes to powerful intermediaries who set the price (OECD 2006).

## Women as land managers

Studies that cast women as less likely to adopt farm technologies are misdirected when they do not consider the inherent disadvantages faced by them. Africa and its women farmers were by-passed by the first Green Revolution in part because of the misconception that they were reluctant to adopt new crop varieties and use mineral fertilizers (Okigbo 1990), when in fact later studies demonstrated that such adoption is the result of economic advantage not gender difference (Gladwin *et al.* 1997). Both traditional value systems and their modern distortions force women to become household providers rather than income earners, in large part because men retain control over cash crops despite women's help in their production (Fortmann 1981). Some misconceptions are based upon women's wiser decision making as when they readily substitute organic inputs for fertilizers or they demonstrate reluctance to accept credit when they fear that needed household food reserves will be sold in order to service loans.

Unequal income and credit opportunities affect the abilities of women to adopt technologies and enter into new farm enterprises. Ironically, this constraint includes the adoption of labor-saving technologies such as inter-row cultivators, wheelbarrows, even donkey carts because men resist paying for equipment that ease tasks that women otherwise provide at no cost (Ashby *et al.* 2008). In some cases, women and men derive income from very different sources (Table 16.1). Other than the sale of farm produce, which is common to both sexes, Ibo women in Nigeria rely more upon gifts, funds from rotating women's groups and paid labor for income, whereas men have greater access to non-farm income and credit (Ezumah and Di Domenico 1995). Consequently, the majority of Ibo women have no understanding of fertilizer while only 25% of men lack this knowledge. Other common constraints to farm productivity faced by African women include reduced availability to land in predominantly patrilineal societies, skewed division of labor as women are responsible for more tedious and time-consuming tasks and less access to farm inputs and extension information, all of which largely result from their cultural obligations toward men and gender norms imposed upon them over many generations. Because of these sorts of disadvantages, women farmers are less able to respond to commodity price and new enterprise opportunities (Evers and Walters 2000).

Table 16.1. Sources of income used for farming among male and female farmers in Iboland, Nigeria (Ezumah and Di Domenico 1995)

| Income source | Female farmers | Male farmers |
|---|---|---|
| | ---------------- % | ----------------- |
| Sale of produce | 49 | 40 |
| Gifts from family | 33 | 10 |
| Rotating funds | 20 | 11 |
| Paid farm labor | 11 | 6 |
| Non-farm income | 4 | 24 |
| Borrowing and credit | 3 | 20 |

On the other hand, agriculture in Africa is undergoing a rapid transformation from traditional, subsistence farming to market-oriented agriculture, and this dynamic has a marked effect upon gender roles within rural households. Fewer distinctions may be drawn between women and men's crops in Ghana and female-headed households readily enter into production of men's cash crops such as cotton, rice and sugarcane (Doss 2002). Women practicing agriculture in migrant areas face fewer gender constraints and find greater opportunities in Nigeria (Ezumah and Di Domenico 1995). The same is true for urban agriculture where women control not only the production of traditional vegetables but also their trading (Kessler *et al.* 2004). New market opportunities that emerge from changing agricultural value chains have indeed improved the standing of women in African agriculture but for them to fully capitalize on

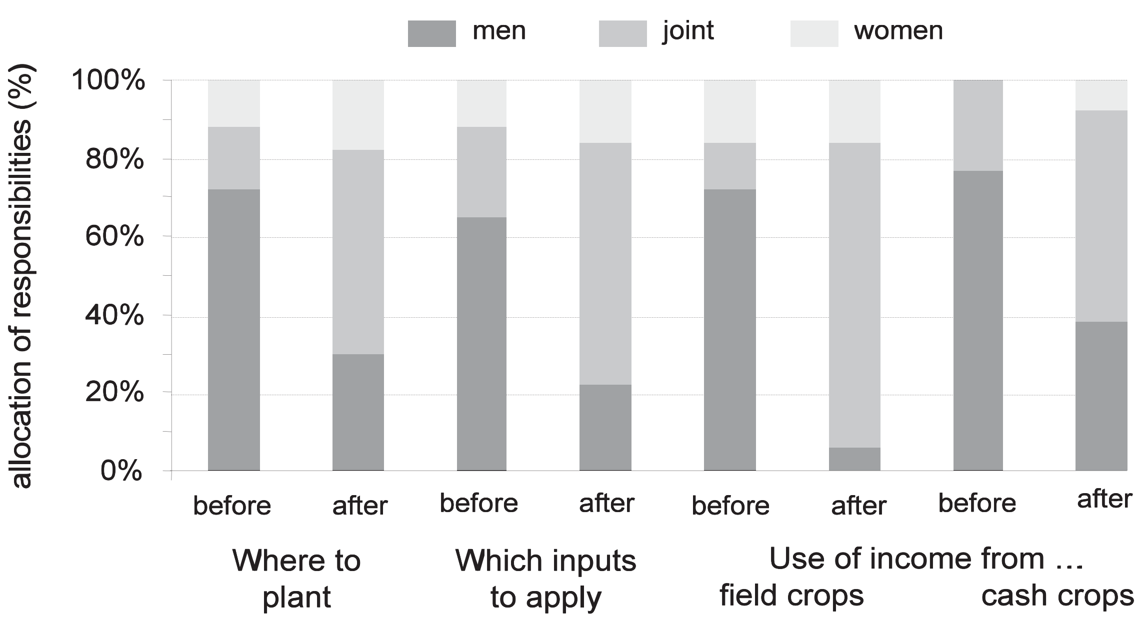



Figure 16.1. The effect of rural enterprise development on household decision making over three years (after Kaaria *et al.* 2008).

Table 16.2. Ranking of nutrient sources used by women and men farmers and reasons for their preference (after Mapfumo *et al.* 2001).

| Nutrient Resource | Ranking by ... women | men | Factors (restrictions) |
|---|---|---|---|
| Inorganic fertilizer | 1 | 2 | Results in immediate and reliable benefits (cost prohibitive) |
| Animal manure | 2 | 1 | Affordable and longer-lasting in soil (requires ownership of substantial livestock) |
| Compost | 3 | 4 | Available from processing local materials (labor intensive to produce) |
| Termite mounds | 4 | 3 | Readily available in fields and long lasting (labor intensive to recover and spread) |
| Agricultural lime | 5 | 6 | Markedly improves groundnut yield (not widely available) |
| Leaf litter transfer | 6 | 5 | (increasingly less available) |

these opportunities they require business development services (Ashby *et al.* 2008).

Several gender-responsive actions are available to improve women's control over resources and access to markets including the promotion of women's collective action and voice within farm associations, cultivating women's profit orientation, protecting women's control over their economic gains and involving them more in the design of rural development projects (Ashby *et al.* 2008). At the same time, gender mainstreaming necessarily involves men. Divisive views that consider men and women in farming households to be operating in separate spheres with coercive interdependency are losing relevance as farms become increasingly oriented toward markets (Evers and Walters 2000). Joint decision making on which crops to grow, which inputs to apply and how to allocate revenues was greatly increased over a relatively short market development program for beans in Malawi (Figure 16.1). Co-responsibility was also strengthened through improved marketing of potatoes in SW Uganda (Kaaria *et al.* 2008). Joint decision making realizes full comparative advantage of the sexual division of labor without leading to exploitive gender roles (Quisinbing 1996).

Differences in women's and men's attitudes toward technologies and their adoption, however, are to be expected. Women's perspectives place greater emphasis upon risk and household vulnerability, time requirements rather than force of labor, and more immediate contribution to household well being. These considerations are also reflected in soil fertility management. In the communal farming areas of Zimbabwe, farmers have a variety of nutrient resources available to them and preference for these resources varies somewhat between men and women (Table 16.2). Women prefer the use of inorganic fertilizer compared to animal manure, in large part because they have little control over livestock (Mapfumo *et al.* 2001). Women prefer composting whereas men prefer to mine and spread termite mounds. Women better recognize the importance of liming groundnut because pegging has an external Ca requirement and women generally control this crop. Note that leaf litter transfer from the dry woodlands is now less practiced as the resource become increasingly less available to households compared to alternative material. Nonetheless, options for soil fertility management are relatively finite within the context of efficient, market-oriented agriculture, and fewer differences in

Table 16.3. Adoption of soil fertility management practices by household heads in Vihiga, Kenya (after Marenya and Barrett 2007).

| Soil fertility practice | Adopters Women | Men |
|---|---|---|
| | ------ % ------- | |
| Manure | 59 | 64 |
| Fertilizer | 44 | 57 |
| Trash lines | 44 | 47 |
| Agroforestry | 24 | 22 |

technical preference may be attributed to gender than other farm characteristics. For example, in a densely populated highland in west Kenya, female- and male-headed household show little difference in the adoption of proven ISFM practices (Table 16.3), compared to other farm characteristics including farm size, value of livestock, family labor supply or education level (Marenya and Barrett 2007). This sort of similarity between women's and men's ISFM practice could readily be ascribed to joint decision making within families responding to the innovations required to address emerging agricultural markets (Evers and Walters 2000; Sanginga *et al.* 2004; Ashby *et al.* 2008). Development specialists now recognize that large impacts are achieved when assistance programs specifically address women's abilities and this opportunity extends into ISFM as well as illustrated through the following examples.

**Distribute inputs samples.** Women are worthwhile recipients of sample fertilizers that are being distributed to promote ISFM practices. Small amounts of fertilizer (e.g. 1 to 2 kg) can have a large beneficial effect on nutrient-deficient home gardens and small fields managed by women. These fertilizers are effectively distributed through women's and youth groups as a way of familiarizing these parties with new technologies and improving their household status. Free fertilizers are not a standalone option, rather they should lead to increased fertilizer demand by poorer households and improved fertilizer marketing by local merchants and farm associations (Gladwin *et al.* 1997; Blackie and Albright 2005).

**Package fertilizer into smaller quantities.** Fertilizers that are packaged in smaller quantities are more useful to women. Normally fertilizers are imported and distributed as 50 kg bags and suppliers must make special provisions to repackage and label them in compliance with quality assurance regulations. Once compliance is secured, local distributors that offer fertilizers in quantities of 2 to 20 kg are providing a valuable service to women who otherwise find it difficult to afford and transport larger quantities. (Omamo 1998, Ashby *et al.* 2008) Women's individual gardening enterprises tend to be sufficiently small that a 10 kg bag of a concentrated fertilizer (e.g. DAP or Triple 16) is sufficient to fertilize between 800 to 1000 $m^2$. This strategy logically follows the distribution of free fertilizer samples to women as a means to promote understanding in ISFM and generating demand for fertilizers. (Gladwin *et al.* 1997)

**Expand women's intercrops.** One means to provide greater access to land by women in traditional settings is through intercropping. Often cash and staple crops grown in the larger fields belong to men while vegetables and pulses are allocated to women (Doss 2002). This separation does not refer to the division of labor, as women are expected to toil in men's fields as well, but rather to which family member receives payment for the crop. As ISFM involves greater reliance upon nitrogen-fixing legumes, and as many legumes are considered to be traditional women's crop, then intercropping with legumes is one means to provide greater equity within the farm. (Gladwin *et al.* 1997)

**Promote small animal enterprise.** Just as there are men's and women's crops, so too is there gender division of farm animals. Men control livestock, particularly cattle, while women are generally responsible for poultry and other small, domesticated animals. The manure from livestock may be similarly allocated with smaller animals producing higher quality by-products (Lekasi *et al.* 1998). One means to channel more organic nutrients to women's farm enterprises is through the promotion of small animals, particularly chickens. Efficient recovery of these manures requires that animals be raised in confinement and provided with higher quality feed. In this way, entering or expanding small animal enterprise requires both initial and regular investment, but it can also offer some of the greatest returns, both in farm profits and the availability of organic fertilizers.

**Introduce organic fertilizer production.** Women are engaged in many household activities that involve the processing of available organic resources, particularly handicrafts. Opportunity exists to channel these efforts toward the improvement of under-utilized organic materials through the production of organic fertilizers. Unlike livestock and green manures, most crop residues are low in nutrients (Palm *et al.* 2001) and require special handling to become transformed into high quality organic fertilizers. One such process is fortified composting, where nutrient-poor crop residues are ameliorated with small amounts of fertilizers or agro-minerals and the mixture protected against nutrient loss in order to produce a valuable organic fertilizer within only four months (Ndungu *et al.* 2003). Another approach involves the use of epigeic earthworms to process farm by-products, crop residues and domestic wastes into rich humus while producing a protein-rich feed for poultry and fish (Edwards 1988; Savala *et al.* 2003). Other lower technology approaches such as pit and layered heap composting are available as well. These organic fertilizers may be produced on individual farms or as a grassroot's collective activity (Kibwage and Momanyi 2003). Resulting composts are best used in seedling potting mixtures or as soil amendments to higher value crops, strengthening the position of women within new agricultural enterprises.

**Offer special incentives through women's groups.** Women's groups serve as an excellent platform to advance many ISFM technologies. Women's groups have several forms, from the 20-or-so member grassroots neighborhood association to the women's chapter of large farmer organizations consisting of hundreds or thousands of members. All such groups exist to provide services to their members including better access to information and technologies, bulk purchase of key farm inputs and collective marketing of produce (see Chapter 18). ISFM technologies may be channeled to farmers through these groups in a number of ways. Extension information and sample products may be distributed at meetings. The groups may be commissioned to install field demonstrations and host farmer field days, or to initiate collective composting or seedling nurseries. Soil fertility management products may be extended on credit to women farmers through their associations and repayment used to initiate revolving funds for following seasons. Similarly, vouchers for the purchase of farm inputs through local stockists may be distributed through these groups. Women may collectively produce needed seed, particularly new varieties of legumes and vegetables for sale to their neighbors, farm organizations or contracting seed companies.

These groups should be registered with local authorities, but not dependent upon them and have regular meetings, elected officials, bank accounts and established contacts via post, telephone and email (Woomer *et al.* 2003). In many cases, these groups not only serve to support vocational agriculture, but also as the center of local social activities, further strengthening members' commitment. One great advantage in working within women's groups, rather than with individuals, is the peer support that strengthens members' commitment and performance. Another benefit is that successful groups tend to stimulate the formation of similar groups in adjacent areas.

Despite new opportunities to advance ISFM by women, numerous asymmetric power relationships continue within small-scale farming households. Women may be ordered by their husbands to hand over farm inputs and credit vouchers or instructed by them to conduct field operations in a time-bound manner. Women in societies that practice child marriage and polygamy are especially vulnerable as they are viewed as laborers supervised by their husbands. In some cases, male household members may simply expropriate successful farm enterprises initiated by women (Ashby *et al.* 2008). Nonetheless, change is underway as more women join grassroots groups catering to their needs. Microfinance associations and community banks specifically target women because they are more responsible borrowers. Furthermore, women are increasingly becoming heads of household as male family members' age, pass away or migrate to urban areas in search of employment, placing these women in a better position as innovators, including the adoption and refinement of ISFM technologies. (Ezumah and Di Domenico 1995)

**Introduce labour saving technologies and transport policies.** Many labor saving and productivity increasing technologies prove to be particularly problematic owing to women's more limited ability to afford and operate them. Consulting women in the actual design of a new technology can effectively make its development more demand driven and dramatically improve the chances of adoption (Ashby *et al.* 2008.) Transport policies are particularly important for ensuring that higher prices actually reach women farmers at the farm gate. Strengthening marketing structures to ease women's access and to improve their terms of participation is critical for sustaining the supply of crops controlled by women (SIDA 1996; UWONET 1995).

**Train and recruit more women as service providers.** Women farmers operate under greater constraints than do men and require specialized assistance. Women generally have poorer access to information, technology, land, inputs and credit (Saito and Weidemann 1990). They also have less available time and mobility because of their responsibilies within the home. Too often, women in rural Africa are less illiterate. Male extension agents lack expertise and interest in rural home economics and efforts directed toward improving household nutrition and stimulating cottage industries are most effective when conducted by women to women (Saito & Weidemann 1990).

The importance of gender of the extension agent in transmitting information to women farmers varies enormously depending on the local cultural context. In Muslim areas, it is not permitted that a male extension agent work directly with women farmers, even where they are eager for advice (Saito and Weidemann 1990). Evidence from a wide range of other African countries demonstrates that communication with women farmers is generally enhanced when female extension agents are used (Evan 1989). This situation is true even in countries with relatively few social barriers to male-female interaction. In Zimbabwe women are legally equal in status to men but more women participate in extension when female agents are involved (Skapa 1998). To avoid domestic tension, however, it is best to enlist the support of husbands and male leaders before embarking on women's agricultural programs of any sort. A study of Igbo women in Nigeria noted that effective extension requires that female extension agents undertake training and visitations so that the cultural barriers are reduced (Ezumah and Di Domenico 1995). In addition, women agents tend to be more sensitive to different abilities and capacities in farm labor among household members.

Gender targeting is particularly useful in bringing extension services to new women farmers. It is consistent with the focus group approach of extension that considers the limited number of female extension agents. Women agents are first assigned to work with women's groups and then gradually introduce the group to another agent working in the area, often a male. The women agent then moves on to another women's group (Walker 1989). This approach requires that male agents also be retrained to work more effectively with women clients. The same conditions apply among women researchers, where new agricultural technologies that are pioneered without the women's perspective become difficult to adopt because they were designed by and for men but ultimately targeted toward women farmers (Ashby *et al.* 2008).

Increasing the employment of women as frontline staff in the delivery of extension, business development, veterinary and environmental conservation services is one of the most effective ways to improve the gender balance in service delivery. Gender policy that establishes and trains both women and men to work in teams as frontline staff supporting women producers has proven effective in India's ATMA program and Venezuela's CIARA foundation (Ashby *et al.* 2008). Replicating the success of such initiatives requires redressing the gender imbalance in all fields and types of agricultural education and training in tandem with targeted recruitment and affirmative action aiming to increase the number of female students, instructors, extension agents, researchers and project managers.

## Farm ergonomics

ISFM substitutes exhaustive and repetitive labor with new skills and greater investment in farm activities. This change is an important component in the transition from subsistence farming to mixed enterprise, market agriculture (Table 16.1) essential for improved standards of living in rural areas. Hand tillage is an example of relievable drudgery. Hand digging cultivates between 50 to 200 $m^2$ per day. Farmers can improve their efficiency of land preparation 20-fold by investment in oxen or by hiring an oxen team or tractor. Furthermore, the culture of animal traction may be stimulated by developing plowing, pulling contests, and livestock awards around it. However, moving from human to animal and machine powered tillage involves not only investment and skills, but also new understandings in smallholder occupational safety. For example, there are situations in Africa where development programmes could usefully promote donkey power for poorer farmers, and especially for use by poorer women. Animal traction or transport packages could be made available to women's groups on credit, where women are engaged in collective cultivation of cash crops, and prove particularly valuable for inter-row hoeing. A majority of poorer women in African countries believe that donkey-traction and transport would suit their needs and they are anxious for related credit and training (IFAD 1998). Planting and weeding are two other field operations that are rendered less labor intensive by investment in simple equipment and tools. (Kaaria and Ashby 2000)

Where fertilizers are in use, additional labor is required to spread and incorporate them, but this work is far less exhaustive than traditional land preparation and the returns to labor and

Table 16.4. Household impacts as farm innovations are adopted by small-scale farmers.

| Current practice | Likely innovation | Impact upon household |
|---|---|---|
| Subsistence intercropping | Mixed enterprise farming | New skills, greater investment, improved marketing skills |
| Hand tillage | Oxen plowing | Less exhaustive labor, investment in livestock & tools |
| | Tractor hire | Payment for service or cooperative investment |
| Little or no fertilizer used | More reliance on BNF | Improved nutrition, investment in seed & inoculants |
| | Use of Agro-minerals | Increased investment and labor |
| | Manure management | Increased labor, substitution for fertilizer purchase, strengthened livestock enterprise |
| | Nitrogen top-dressing | Increased investment and labor, new skills |
| Hole planting | Open furrow planting | Less repetitive labor, greater reliance upon livestock & tillage implements |
| | Mechanical line planter | Less repetitive labor, investment in small equipment |
| Hand weeding | Lighter "cutting" hoe | Less exhaustive labor, wider gender participation |
| | Herbicide wick or sprayer | Less exhaustive labor, investment in technology |
| Field storage | Crib storage | Higher grain quality, some additional family labor, rodent prevention |
| Hand shelling | Rotary shelling | Less repetitive labor, investment in small equipment |
| | Machine shelling | More broken grain, cooperative investment |

investment are large. The management of fertilizer nitrogen in particular requires new sets of skills to position the fertilizers and prevent their gaseous loss through combined top-dressing and weeding operations (Table 16.4). Improving crop harvest and processing operations also requires investment that substitutes for repetitive labor and is often necessary before crop quality can meet the industry standards of top-end buyers. One exception to this is the increased reliance upon mechanical grain shellers that do not differentiate off-grade grains and result in increased broken grains. New skill sets are necessary to operate this equipment in an effective and safe manner.

A key to improving human capital and reducing drudgery is through the new roles open to women and children. Musculoskeletal disorders are common among agricultural workers and may yet increase as labour intensive agriculture expands (Villarelo and Baron 1999). Women's physiology makes them especially vulnerable to farm-related ill-health and risk reduction in this area has large beneficial impacts upon the household as a whole. While men frequently shoulder the heaviest jobs, women and children are too often expected to perform lengthy and repetitive tasks with little regard to ergonomics. For example, weeding operations with heavy digging hoes is unfair to weaker members of the family considering that lightweight cutting hoes are known, if not readily available. The same may be said for planting and shelling where popular innovations can greatly reduce necessary labor. One impact upon market-oriented farming is its need and respect for knowledge and this raises regard for education, both by children and adults. Poorer households are more willing to send children to school when their educations are seen as essential to escape from poverty. Similarly, participation in youth and women's groups are also viewed as avenues of important information. In addition, when labor requirements are reduced, more time is available to assist the disadvantaged, particularly widows and the elderly, in completing their most arduous field operations. In this way, more efficient and profitable farming can also become more equitable and charitable.

**Occupational safety and responsible treatment of hired labor**

Human conditions may be improved through farm occupational safety. Smallhold farms are businesses that rely upon family labor backstopped to varying degrees by hired workers. In traditional farming systems, soil management practices are among the most difficult tasks, both in terms of drudgery and tedium. Particularly the poorer households lacking oxen or the funds to hire animal traction perform much land preparation by hand using crude hoes. Weeding is a tedious task that is usually performed by hand or with inappropriate tools, requiring workers to perform repetitious physical labor at rapid paces and in difficult postures. On average, men are better suited to perform these field tasks because of their greater musculature and cardiovascular capacities. Women and children expected to perform these same tasks often suffer ill effects to their muscles, skeletons and internal organs. In addition, women have a greater proportion of fat that absorbs more pesticides. Pregnant and breast-feeding women are affected most (Jafry 2000).

Smallholders' field operations are performed with little regard to farm occupational safety when the elderly, women and children are expected to perform tasks that exceed their physical stamina. Hired workers, recruited to fill needs that family labor cannot perform are often treated in the same manner. To be widely adopted, ISFM practices should not demand unrealistic tasks but rather develop in a manner that assures gender equity. The types and interactions among farm enterprises, soil conditions, investment opportunity in external farm inputs and tools, and the availability and stamina of family labor and hired workers determine specific ISFM practice. Some guidelines that promote farm occupational safety and gender equity follow.

1. Family farms will necessarily continue to engage household labor, including children but the tasks must be proportionate to members' strength and stamina. Despite household labor

needs, children must be permitted, indeed encouraged, to attend school. School schedules in rural areas should reflect the peak labor needs of surrounding farms.
2. School curricula should include vocational agriculture and ISFM practices. Schools should maintain demonstrational gardens and students encouraged to explain agricultural technologies to their families. Technology adoption campaigns must include schools.
3. Ergonomics within smallholder farms warrants further attention by agricultural researchers, tool producers, extension agents and rural development specialists. Most farm households make and affix their own wooden handles to metal farm tools and they should be advised concerning their better design. Heavy and repetitive work conducted in awkward positions must be minimized.
4. Occupational health not only involves risk avoidance but also treatment and therapy. Workers experiencing acute or chronic muscular, skeletal or internal pains require medical advice. At the same time everyone feels a hard day's work and care must be taken to relax following several hours of heavy labor so that small aches do not grow into medical conditions.
5. ISFM and its labor-saving facets must be advanced within rural development agendas. Incentives should be provided to farmers seeking to convert farm operations toward more mechanized agriculture. Other labor-saving technologies, such as minimum tillage, require new sets of skills and field equipment that are not presently available to many farming communities.
6. Pesticide applicators must receive training and use protective gear. Applicators must be particularly aware and careful when they are handling dangerous pesticides. Children must never apply pesticides nor be permitted to handle protective gear or sprayers until they have been cleaned. Pesticides must be stored and disposed in areas inaccessible to children.

Table 16.5. Contributions of ISFM toward the Millennium Development Goals.

| Millennium Goal | ISFM contribution | Comments and implications |
|---|---|---|
| Eradicating extreme poverty & hunger | Increased household & national food supply and enjoy larger incomes from more profitable farming | Farm profits become recycled through the rural community (Cabral *et al*. 2006; Sanchez *et al.* 2007) |
| Achieving universal primary education | Less dependence upon child labor on the farm, greater appreciation of knowledge | ISFM practices must be explainable to those with a primary education |
| Promoting gender equity & empowering women | Less arduous and repetitive labor by women, greater occupational safety | As new tasks emerge, traditional division of labor must be abandoned |
| Reducing child mortality and improving maternal health | Improved diets as farm enterprises diversify and household income grows | Better crop nutrient management improves mother and child nutrition as well |
| Combating HIV/AIDS, malaria & other disease | Improved diets for the ill, labor and input donation to the disadvantaged | Illness diverts household income away from farm investment toward medical treatment |
| Ensuring environmental sustainability | Increased farm biodiversity, improved soil and water quality, reduced crop disease | Many ISFM practices result in net carbon offsets, reducing global warming |
| Developing global partnerships | ISM becomes prominent within rural development agendas | ISFM advances from a scientific discipline into a developmental strategy |

## Role of ISFM toward attainment of the Millennium Development Goals

One means to assess the role of ISFM toward gender equity is through its potential contributions to the Millennium Development Goals (MDGs). These goals were established at the Millennium Summit in 2000 in order to set an international standard in addressing improvements in the quality of life within developing countries (Juma 2006). The MDGs include eradicating extreme poverty and hunger, achieving universal primary education, empowering women, reducing child mortality and improving maternal health, combating HIV/AIDS, malaria and other disease and ensuring environmental sustainability with specific targets identified for the year 2015 (UN Statistics Division 2005). Where applied to farming communities, integrated approaches to soil fertility management make a positive contribution to many of these goals (Table 16.5).

The contributions of ISFM toward poverty eradication and environmental sustainability are described in detail elsewhere in this book. It is in the fulfillment of the other equally important MDGs where ISFM plays a more subtle and sometimes overlapping role. ISFM seeks to substitute skills and investment for arduous and repetitive labor, thus providing incentives for primary education and greater occupational safety for women and children. As farm enterprises diversify and household income grows, household diet improves in a manner which benefits expecting women, young children and the ill.

Some negative impacts may also occur, particularly in regard to combating HIV/AIDS, malaria and other disease. Sickness and death can result in labor shortages leading to reduced land under cultivation and declining yields. In many areas, children learn about farming by working alongside their parents. Because of gender division of labor and knowledge, the loss of even one parent can inhibit the transfer of skills. Farming households affected by HIV/AIDS and chronic illness are forced to divert limited incomes to medical treatment, precluding investment in needed farm improvements (Baylies 2002). In the worst affected households, farming may be abandoned altogether (Slater and Wiggens 2005). From these negative consequences, it is important that ISFM measures focus upon labor-saving technologies and be accompanied by strong educational campaigns if they are to fully contribute to gender equity within the Millennium Development Goals.

It is excessive to refer to ISFM as a livelihood strategy but indeed, it can be a key component to small-scale farming. Greater reliance upon legumes and mixed farming not only improves the soil, but also the protein, vitamin and micronutrient contents of household diets are upgraded (Manson *et al.* 2001). Soil conservation improves soil tilth, reducing the labor requirements of land preparation. Surface mulching and vegetative groundcovers not only protect soils but reduce crop maintenance, particularly weeding operations (Roose and Barthès 2001). ISFM offers a win-win situation in terms of land quality and labor requirements that are readily passed on to disadvantaged household members. Greater and more efficient crop production may increase the labor required for harvest and crop processing, but for farmers this is a labor enjoyed because it represents household security (Rahman *et al.* 1993). Furthermore, more profitable farming permits greater dependence upon hired labor during peak demands. These sorts of benefits are spread across household members in a manner that offers less drudgery and greater incomes, and in this way ISFM is gender-friendly.

# Chapter 17. ISFM and household nutrition

While the immediate objective of ISFM is to provide nutrients to plants as a means of increasing crop yields, the ultimate goal is to improve the living conditions, food security and nutrition of farm households (Borlaugh 2003). The poor rural household consumes maize or other traditional grains daily but they eat beans, wheat and rice only once or twice per week and enjoy meat only on special occasions. Surprisingly, many maize producing households suffer shortfalls in their preferred staple because food needed over the next few months must be sold to meet demands that are more pressing. Ironically, many households may then spend most of their available cash to purchase the same commodities that they had months earlier produced and sold.

Not only food insecurity, but also the quality of diets in Africa requires urgent attention. Poor diets are defined as those that do not supply the essential, balanced nutritional constituents providing energy, protein, vitamins and minerals. Many diseases in poorer households are induced by incomplete diet and seasonal malnutrition. Many crops rich in starch are low in protein and other nutrients essential to human health (Johns 2003). Protein deficiency, also known as kwashiorkor, is all too prevalent in populations throughout rural Africa. This deficiency in foodstuffs results in part from insufficient nitrogen and sulfur for synthesis of amino acids by crops, which in turn relates to poor soil fertility management. Poor food quality in Africa is further complicated by the so-called hungry harvests. Crop harvests may be rich in starch but contain insufficient amounts of protein, vitamins and minerals that are required by the human body. To emphasize this point, Davis *et al.* (2004) reported a marked reduction in the nutritional quality in 12 common vegetables between 1950 and 1999 caused by changing agronomic practices. Another concern is seasonal malnutrition caused when poor households lack harvestable crops in their fields and have insufficient income to cover the food shortfall.

ISFM provides several entry points for increasing and diversifying human diets. Its reliance upon field legumes as sources of symbiotically fixed nitrogen allows cultivation of more intensive and more diverse food legumes that in turn improve the supply of vegetable protein. More closely integrating crop and livestock enterprises not only tightens nutrient cycles but also increases the supply of animal proteins available to the household. Improved soil fertility also enhances the nutritional balance of foods, including their mineral and vitamin contents. Diversifying crop enterprises also improves household diets, especially when new vegetables, tubers and fruits are produced in addition to staple grains. In some cases, raising food quality does not assure better diets without accompanying food processing technologies that protect nutritive value. For example, nutritive crops that require processing such as soybean may be grown for the market and bypass producing households unless training and incentives are offered for localized value-added processing. In other cases, non-food green manures may be grown for their soil benefits alone, and farmers must then take advantage to diversify their food production enterprises the following season. In this way, ISFM does not necessarily improve household nutrition, but rather it provides opportunity for informed homemakers, both farmers and consumers alike, to provide their families with more food and better diets.

Complex relationships between household diet and ISFM are revealed through interpretation of a household survey conducted in West Kenya during 2005 (Table 17.1). The overall purpose of the survey was to identify produce marketing opportunities among smallhold farmers but respondents were also queried concerning their soil fertility management practices, farm diversification and household wellbeing. Farms were grouped by resource endowment and household characteristics expressed (Shepherd and Soule 1998). All of these farms practice maize-bean intercropping as the main farm enterprise (Table 17.1). Resource poor households occupy smaller farms, practice fewer farm enterprises, own fewer domestic animals and use less mineral fertilizers. Poorer households also tend to better manage organic resources within their farms in a manner consistent with ISFM, particularly making better use of manure and legume intercrops, but their ability to combine these practices with top-dressed mineral fertilizer is

Table 17.1. Household characteristics among 247 small scale farm in west Kenya (F.M. Mwaura, 2005, unpublished).

| Parameter | Resource Endowment | | |
|---|---|---|---|
| | Poor | Modest | High |
| Farm size (ha) | 0.4 | 0.9 | 3.8 |
| Household size (members) | 7.1 | 7.6 | 9.4 |
| Proportion of maize on farm (%) | 67 | 67 | 49 |
| Apply pre-plant fertilizer (%) | 45 | 63 | 90 |
| Apply top-dressed fertilizer (%) | 7 | 27 | 49 |
| Apply manure (%) | 32 | 16 | 13 |
| Practice innovative intercropping (%) | 35 | 13 | 10 |
| Number of cattle | 0.5 | 1.9 | 5.5 |
| Number of poultry | 8.4 | 9.3 | 16.7 |
| Produce potatoes or sweet potatoes (%) | 13 | 19 | 35 |
| Produce bananas (%) | 5 | 12 | 45 |
| Consider themselves food secure (%) | 14 | 34 | 53 |
| Meals served with maize (per week) | 9 | 8 | 8 |
| Meals served with beans (per week) | 2 | 2 | 2 |
| Meals served with milk (per week) | 6 | 8 | 10 |
| Funds spent for medicines ($ per week) | 0.47 | 1.15 | 6.35 |
| Belong to farmer associations (%) | 49 | 63 | 68 |

considerably reduced. It is important that very few of the least endowed households considered themselves food secure despite strong similarities in household diet. Note that better endowed households appear to have much better access to animal proteins and to have greater ability to respond to household needs. These sorts of findings present a challenge to proponents of ISFM because improved household nutrition is not necessarily reflected in better soil fertility management among the least endowed households, suggesting that ISFM promotional activities should include a component where farm diversification, especially expansion of legume cultivation and animal enterprise, bringing corresponding improvement in household diet.

Clearly, the best way for smallhold farmers to improve the quality of their diets is by growing and consuming a wider variety of foods, particularly those rich in protein and vitamins. The higher protein content and variety of vitamins contained in fruits, nuts and vegetables offer obvious solutions. These approaches to dietary improvement do not necessarily involve the integration of ISFM into farm operations when these crops are cultivated in small, isolated plots. ISFM interacts heavily with household nutrition in two major areas, however, through the intensification of cultivating symbiotic grain legumes and through the improved nutritional quality of harvests resulting from more balanced soil fertility management.

**Benefits from legume intensification**

A key to ISFM practices by many small-scale farmers is the combination of staple cereals and nitrogen-fixing legumes as intercrops or in rotation. This reciprocation is matched by nutritional complementarily of cereal and legume protein, a phenomenon that was discovered empirically throughout the tropics. Diets of rice and soybean in Southeast Asia, millet and pigeon pea in dryland India, sorghum and cowpea in Africa or maize and beans in Central America all illustrate this point (Hulse 1991). Ideally cereals and legumes should be consumed in a ratio of 70:30 in order to consume equal amounts of vegetable protein and to achieve a desired balance of amino acids. Unfortunately, this goal is not met with households producing and consuming a disproportionately greater measure of cereal and other starches. This trend is based not only upon the relative productivity of cereals, which is greater under low management regimes, but also due to market forces which generally process cereals into a wider range of products than legumes. Legumes are able to be processed into numerous products, however, and the development of new, and expansion of existing food technologies for legumes remains a major goal for developing countries (ICRISAT 1991). When placed into the needs of small-scale farming households, these market opportunities and a shortfall in legume protein offers an important signal for adoption of ISFM.

Table 17.2 Food composition of legumes important to ISFM[1]

| food legume (*scientific name*) | edible part | Protein | fat | carbo-hydrate | Ca | P | K | Vit A | Thiamin | Vit C |
|---|---|---|---|---|---|---|---|---|---|---|
| | | ----- propotion dw----- | | | ---------------- mg per 100g ---------------- | | | | | |
| groundnut (*Arachis hypogeae*) | seed | 0.25 | 0.48 | 0.25 | 52 | 438 | | 16 | 0.84 | 1 |
| pigeon pea (*Cajanus cajan*) | seed | 0.22 | 0.01 | 0.73 | 179 | 316 | | 61 | 0.8 | |
| | green pod | 0.24 | 0.02 | 0.69 | 202 | 489 | 1748 | 407 | 1.24 | 90 |
| soybean (*Glycine max*) | seed | 0.39 | 0.2 | 0.36 | 245 | 606 | 999 | 11 | 0.73 | 0 |
| | sprout | 0.42 | 0.1 | 0.43 | 251 | 580 | 467 | 11 | 0.74 | 0 |
| hyacinth bean (*Lablab purpureus*) | seed | 0.25 | 0.02 | 0.69 | 600 | 400 | 2232 | 1280 | 0.64 | 128 |
| common bean (*Phaselus vulgaris*) | seed | 0.25 | 0.02 | 0.69 | 137 | 368 | | 11 | 0.42 | 2 |
| | green pod | 0.22 | 0.02 | 0.7 | 350 | 300 | | | | |
| | leaf | 0.27 | 0.03 | 0.5 | 2076 | 568 | | 24559 | 1.36 | 834 |
| green gram (*Vigna radiata*) | seed | 0.26 | 0.01 | 0.69 | 118 | 370 | 7 | 62 | 0.59 | 4 |
| | sprout | 0.42 | 0.02 | 0.5 | 152 | 717 | 2242 | 202 | 1.11 | 182 |
| cowpea (*Vigna unguiculata*) | seed | 0.26 | 0.02 | 0.69 | 124 | 432 | 777 | 11 | 0.67 | 1 |
| | green pod | 0.33 | 0.05 | 0.55 | 478 | 522 | 1947 | 4027 | 1.24 | 212 |
| | leaf | 0.36 | 0.03 | 0.5 | 664 | 964 | | | 3.18 | 327 |
| bambara nut (*Vigna subterranea*) | seed | 0.18 | 0.07 | 0.72 | 94 | 293 | | 0 | 0.2 | 0 |

[1] Expressed on a dry weight (dw) basis. Based primarily upon Duke 1981.

Food legumes that are well suited to mixed and cereal-based farming systems of the tropics offer excellent sources of not only protein and starch, but also fat (oil), minerals and vitamins (Table 17.2). These nutritional benefits result from the versatility of legumes as sources of edible leaves, green pods, unripe seed, grain and sprouts. In addition to those essential nutrients presented in Table 17.2, legumes also contain significant amounts of fiber, sodium, iron and the vitamin B complex.

The potential for processing and consuming food legumes is great (Figure 17.1). Fresh or dried leaves of cowpea may be steamed or boiled (Maundu *et al.* 1999) and served alone or in combination with other ingredients. Leaves of *Crotolaria ochreleuca* may be prepared in the same way (Woomer 2002). Drying picked leaves greatly reduces their perishability as the leaves readily rehydrate. Slight wilting is not a problem, however, as leaves prepared in this state offer better consistency of the final product. The immature green pods of many legumes may be cooked and consumed including those of cowpea, pigeon, lablab and green bean. Pods are also processed by canning and freezing. The full sized but immature green seeds of several legumes may also be shelled and then cooked or processed, including those of groundnut, cowpea, pigeon pea and soybean. Dried grain can be either soaked and cooked, or ground into flour and grit. Legume flour is often combined with cereal flour to increase its protein content. Grain also serves as a source of seed for future planting. Note that legumes serve as important sources of animal feed as well. Not captured in Figure 17.1 is the pressing of oilseed, particularly groundnut and soybean (see Table 17.2). This process produces vegetable oil and press cake, the latter is an important component of animal feeds. In Asia soybean and other pulses are processed into several additional products including soy sauce, nato, tofu, tempeh and noodles. Some of these products require fermentation, a process also not captured in Figure 17.1.

Legume intensification is intended not only to increase crop productivity, but ultimately to improve farm livelihoods in terms of income, nutrition and health. Adoption of multi-purpose crops such as promiscuous soybeans will lead to better soil quality and increase of yields of subsequent crops. Farmers are also able to process some of the legume harvest for home consumption thus improving the nutrition of household members, especially children who are more disposed to malnutrition.

Grain legume processing and utilization involves the training of trainers, farmers, support groups and community based organizations that results in a ripple effect whereby peoples' diets diversify and protein availability and quality improves. ISFM strategies, particularly cereal-soybean rotation, serve to supplement traditional staple cereals. Because of its pronounced effect on nutrition and health, poorer farmers readily adopt soybean utilization. With time, surplus production sold or processed into products that generate additional income. This adoption boosts economic wellbeing of participating households leading to diets that counteract HIV, hunger and malnutrition in sub-Saharan Africa (Friis and Michaelsen 1998).

**Plant and human nutrition**

Healthy plants are richer in micronutrients and vitamins required in the human diet including calcium, potassium, phosphorus, iron, beta carotine (Vitamine A), the Vitamine B complex (e.g. Thiamine, Niacin, Riboflavin) and ascorbic acid (Vitamin C). The effectiveness of various agricultural measures in increasing nutritional value depends on soil characteristics, crop cultivar, and other factors, thus necessitating development of a specific set of measures for individual agro-ecological zones. In this way, the potential to enhance micronutrient and vitamin concentrations of food through balanced crop fertilization features into ISFM design and decision-making.

Fertilizer application on a world scale is largely dominated by the need to provide crops with the macronutrients N, P and K. Better supply of these macronutrients increase crop biomass and in effect increase the assimilation of other non-limiting nutrients also required by crops and their consumers. In the same way, however, increased demand for secondary and micronutrients may lead to the expression of new deficiencies when their supply becomes limiting (Slingeland *et al.*

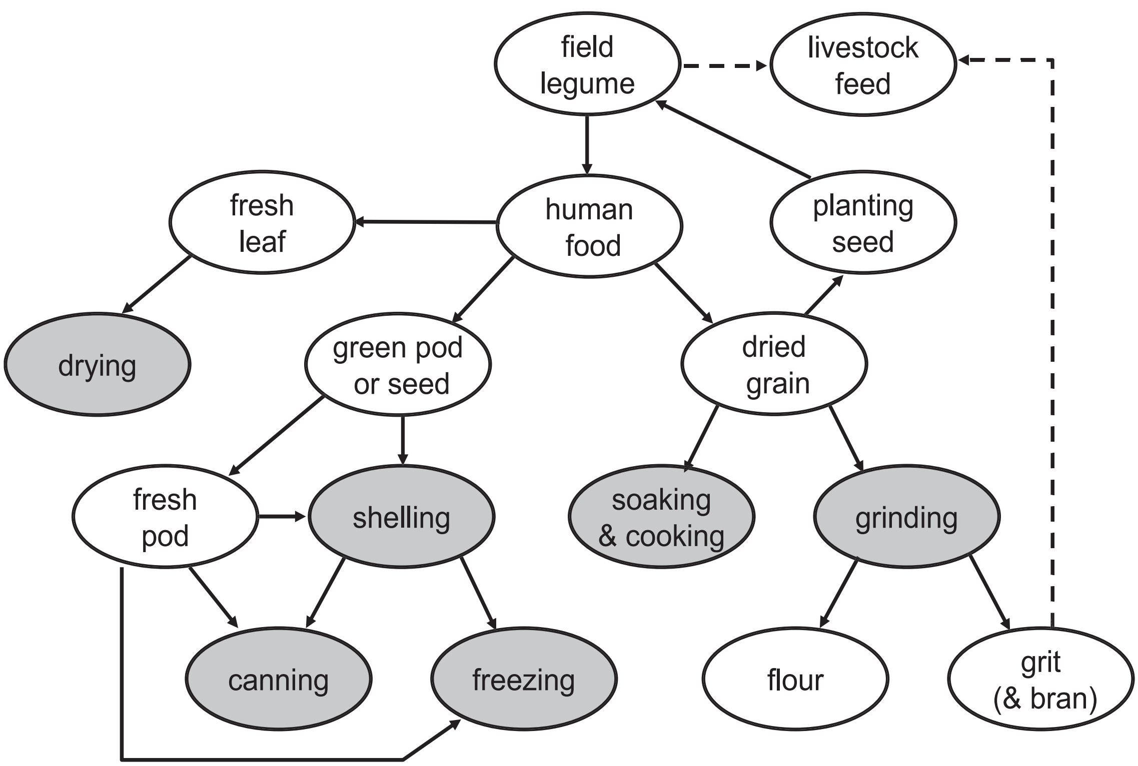



Figure 17.1. Products and processing options (shaded) of grain legumes useful in ISFM. Note that processing options do not consider pressing of groundnut or soybean as oilseed.

2006). Most human mineral needs can be supplied by eating a balanced, diverse diet and, should plant micronutrient deficiencies be expressed, it is important that land managers recognize and correct this condition (see Chapter 6). Studies across many countries in sub-Saharan Africa indicate that many soils are deficient in Zn and Fe once macronutrient status is corrected (Sillanpa 1990). Many fertilizers and agro-minerals contain secondary nutrients in carrier materials and micronutrients as containments (van Kauwenberg 2006; van Straaten 2002). Almost by definition, higher quality organic amendments such as green manures, livestock manures and composts contain required nutrients in the proportion they are required by plants (Palm *et al.* 1994, 2001). Acutely deficient soils can be fertilized with the required secondary and micronutrients to address specific plant and human nutritional demands (Boius *et al.* 1999; Manson *et al.* 2001).

In the case of N, S, P, and the major base cations Ca, Mg and K, there are well established relationships between use of mineral fertilizer, or measurement of available concentrations in the soil and plant uptake of these minerals as demonstrated by the QUEFTS model (Janssen *et al.* 1990). If cations added in fertilizers are not well-balanced, there can be negative interaction on uptake of the other. For example, excess K supply can result in decreased uptake of Mg (see Chapter 4). Relationships between plant uptake and translocation to the grain is less clear. The availability of Fe is not influenced directly by adding it to the soil or plant unless it is in a chelated form. This is because Fe is readily precipitated as oxides that are poorly soluble. Thus there is no sense in adding Fe as mid-season fertilizers to increase Fe uptake by crops (see Figure 17.2). Some nutrients (e.g. Ca, Zn, Fe) are transported through the plant by the xylem, but are relatively immobile in the phloem. This means that they are not readily loaded into accumulating storage organs. Selenium (Se) and iodine (I) are not classified as essential element for plant growth, but both are essential elements in human health. The Se concentration in plants varies considerably and provides a good indication of its availability in soil. Several countries in Africa have documented low Se areas. These include Zambia, Zimbabwe, and DR Congo.

The need for a package of health and nutrition services including micronutrient supplementation (vitamin A, iron and iodine) and nutrition education cannot be overemphasized whether in schools or community setting. Iron deficiency is the most common form of micronutrient deficiency in school-age children and caused by inadequate diet and infection. More than half the school-age children in low-income countries are estimated to suffer from iron deficiency anemia. Iron supplementation of children led to a reduction of anemia (Sifri *et al.* 2003), but the same goal may also be achieved by consuming greens rich in Fe.

Vitamin A deficiency causes impaired immune function, increases risk of mortality from infectious disease and is a leading cause of blindness. Recent studies suggest that this deficiency poses a major public health problem among school-age children in Africa. Vitamin A supplementation of school children and under five year olds in Suba, Kenya improved their general health (Kamau *et al.* 2008). Studies show that multiple-micronutrient supplements have improved cognitive function and short-term memory in school children and have reduced absenteeism caused by diarrhea and respiratory infections.

Further studies are required to examine the potential for addressing the nutritional quality of edible products by micronutrient fertilizer management. Better understanding the factors which influence the nutrient balance is important when selecting for accumulation of a specific nutrient. For example, application of Zn increased grain concentrations in various cereal crops by a factor of two to three, depending on species (Rashid and Fox 1992) and crop genotype (Graham *et al.* 1992). Soil type also influences the extent of increase in Zn concentration in grain as a consequence of soil Zn fertilization. It is important to note that regardless of the yield level or intensity of cultivation, not all the valuable components of a crop product can be increased simultaneously. Where the starch concentration of grain is increased, the protein concentration or another component may be lowered, or vice versa. An increase in the total amount of vitamins per plant may result in lower percentage concentrations owing to the dilution caused by relatively

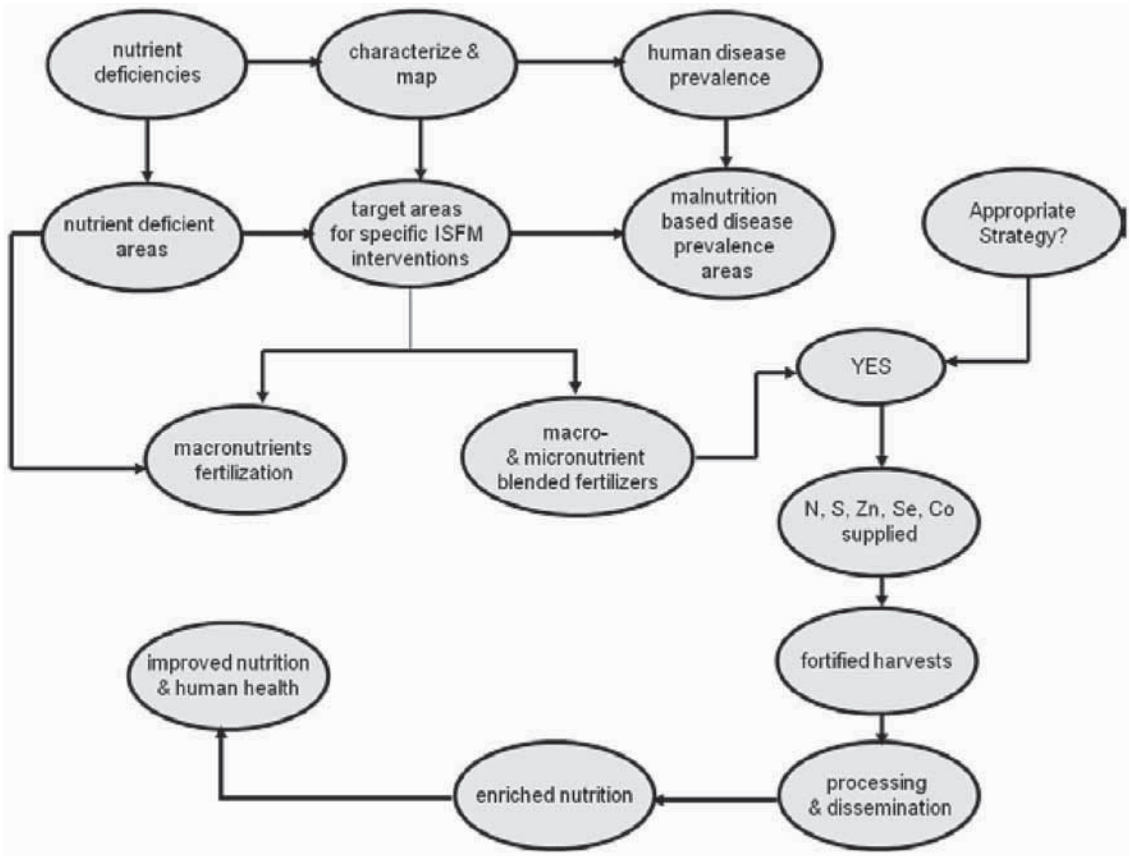



Figure 17.2. The conceptual pathway for impact oriented plant and human nutrition on food quality and health

higher starch and protein concentrations or biomass. The dilution effect is important in characterizing food quality.

## Advancing ISFM and human nutrition

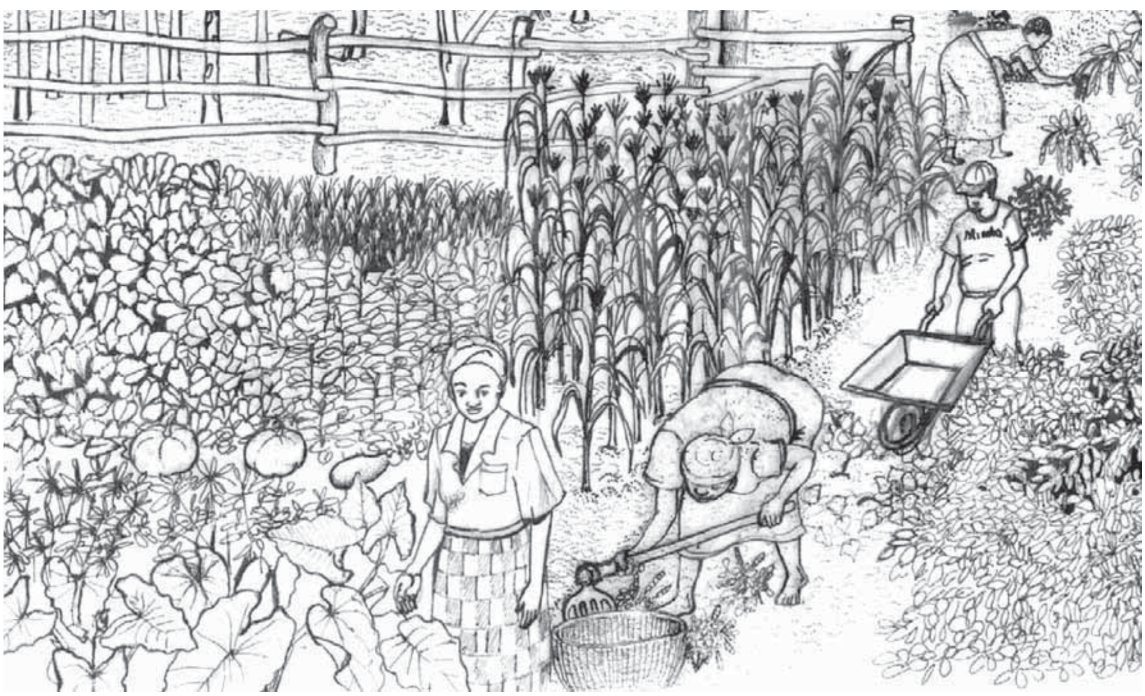
There are two potential scenarios that can occur in different areas; 1) nutrients essential for plant growth are both limiting and deficient in the human diet and 2) human mineral deficiencies are prevalent but the deficient minerals are either not essential for plant growth, or not limiting plant growth. The promotion of fertilizer-based approaches in addressing human mineral deficiencies is different for each of these cases. In the first situation, there is a clear need for new fertilizer blends and promotion of fertilizer-based approaches without involvement of the health industry. In the second situation, strong advocacy from all sectors and cooperation of the health sector are necessary to supplement the fertilizer-based approaches.

One means to simultaneously promote ISFM and human nutrition is through the strategic establishment of community resource and learning centers. The centers serve as technology dissemination points, information repositories and meeting venues. Information campaigns in print, electronic, audio, and visual media may be developed by the food industry, schools, health institutions, religious and social institutions, NGOs, and researchers. Qualified staff must be appointed to dedicate their time in awareness creation, database management and information exchange.

A key to the success of ISFM is the acceptance of new grain legumes by farm households. Bean stews are a major component of smallholder's diet and to a large extend ISFM requires that practitioners extend their consumption to include soybean, gram, lablab, pigeon pea and other pulses. One reason beans are popular is because they cook quickly after soaking and the stew compliments cooked maize meal and other starches. Demonstrations may be conducted that exhibit the convenience and palatability of these other pulses and their processed products. These actions must be supported by the distribution of pamphlets that contain information on household recipes and held in conjunction with farmer field days and community resource centers.

Grain legume cooking contests may also be organized. Briefly, the contest is announced and recipes are solicited. Promising applicants are then selected, the contest scheduled and contestants provided similar cooking facilities. Prior to the contest, each contestant provides a list of ingredients and recipe that is compiled and published as a cookbook. After a specified period, a panel of judges assesses the taste, appearance and originality of the recipes. The contest winners receive a modest cash prize and cooking utensils. This type of contest is a crowd pleaser as observers are then invited to taste the final products. Detailed rules for similar cooking contests appear in Woomer (2002).

School meal programs support both child nutrition and education goals (McGuffin 2005). However, to provide safe and nutritious foods to children requires trained personnel in terms of food handling, sanitation and storage and optimal preparation. Successful programs in nutrition and health education carried out in Africa target specific needs with precise, accurate, relevant and compelling training materials (Probate *et al.* 2003). While ISFM may not have been designed as a vehicle to improve human nutrition and health, when placed into a proper developmental context it serves as a means to increase the diversity of household diets, particularly with regard to increased consumption of grain legumes, and to improve the nutritional quality of foods produced, consumed and sold by the farming household.



# Chapter 18. Capacity building in ISFM

The need for capacity building in ISFM is great, but not overwhelming. On one hand, much knowledge is available on how to better manage soils at the farm and catchments levels (Gachene and Kimaru 2003; Kanyanjua *et al.* 2000) and what is required is the translation of these findings into straightforward farm guidelines and community action plans. On the other hand, capacities in soil science and resource management are deteriorating within national institutes, universities and agricultural extension systems remain poorly financed and hugely overburdened by the sheer number of smallhold farming clients (Swift and Shepherd 2007). An expedient means to mobilize existing knowledge is to identify which stakeholder groups require what sort of information and experience, to prioritize these stakeholder groups and to design and conduct cost effective training exercises that translate findings into information packages and field practices (Woomer 2004).

## Vocational training in ISFM

The ultimate client of vocational training in ISFM is the farming household, although their large numbers and educational backgrounds do not permit them to be gathered and informed en masse. Important intermediate stakeholders that serve as more ready clients of existing practical technologies in ISFM include primary and secondary school students and teachers, officers of grassroot and farm organizations, frontline extension agents and their supervisors and private sector dealers in agricultural inputs. The needs of these stakeholders may be broadly grouped into the category of vocational training.

**Primary and secondary school systems.** School age children are receptive targets of vocational training in land management because they are literate and occupy a respected place within the rural household. Targeting technology demonstrations or community field days to schools allow for large numbers of farmers to be mobilized by their own and neighboring children and for teachers and school administrators to provide peer support and professional expertise to recommended farm practices. One particularly useful way to introduce extension recommendations is through school farming projects, where key inputs are distributed to school administrators, installed and managed by students, resulting produce used to improve school lunches and seed and information materials conveyed to parents (see Chapter 17). Prizes may be awarded to the best efforts during school functions. Furthermore, high school students are usually the most literate members of their family and often have computer skills. The internet revolution is now penetrating even the most remote farming communities, and making useful web addresses known to students is one means of spreading extension information to small-scale farmers. Indeed, disseminating agricultural extension messages via the internet has now become commonplace in developed countries and this cost-effective form of technology dissemination must not be overlooked in developing ones as well. On the downside, secondary education in rural areas is too often seen as a means to escape the drudgery and poverty of small-scale farming and vocational agriculture does not occupy an important position within curricula or student interest.

**Farm association officials.** The elected officials of farmer organizations and grassroot community groups serve as expedient conduits of recommended practices, in large part because they have been specifically elected by members to do so. The elected officials of these groups tend to be the more educated and ambitious group members, often retired civil servants or local school teachers, and understand the importance of accessing extension information, sample input products and new marketing and value-adding opportunities (Chirwa *et al.* 2005; Stringfellow *et al.* 1997). In most cases, these officials are early adopters of numerous promising technologies and their farms serve as neighborhood models of mixed enterprise agriculture. An expedient means of dissemination is to contract farmer associations to install field demonstrations using technology packages accompanied by straightforward field protocols. Association members are required to install one or more core recommendations but also encouraged to modify them or include other practices as they see fit. The demonstrations should be monitored and the most successful of them upgraded to full farmer field days through additional and modest support. Distributing diverse information materials, inviting extension supervisors and agro-dealers, and arranging for local entertainment improves interest in the field days but care must be taken not to distract from the central messages. Focus may be preserved by halting all peripheral field day activities during the display and discussion of the main field demonstrations.

One risk of investing too heavily in technology dissemination through long-standing officials of farm organizations is the self-importance placed upon their positions. Some officials will take entrenching opportunity from collaboration with agents of rural change and even cause groups to fragment should they not be re-elected. For this reason, it is important for development networks to work with at least two officers from each organization and to establish liaison with some of the groups' regular members. Communication with officials and regular members alike is readily achieved via mobile telephones and electronic mail (Woomer *et al.* 2003). Another danger is that the poorest farming households are unable to afford membership dues to farm organizations and may be bypassed by efforts directed through farm organizations. This risk is lessened when working with more localized youth and women's' groups and increased when collaborating with farmers' produce and marketing associations.

**Extension officer updates.** Extension officers are obvious clients for capacity building in ISFM and, if they are better positioned to fulfill their designated roles in rural transformation as trainers, the role of other less accessible stakeholder groups would decrease. In fairness, ISFM technologies are complex and extension service providers, whether extension agents or farm liaison specialists placed with NGOs and the private sector, are too often unprepared to backstop developmental efforts in this area. Furthermore, ill-informed agents may extend inaccurate or conflicting messages to farmers and must therefore be empowered to understand and deliver key messages through cost-effective training exercises.

To better understand the failure of frontline extension, one must better appreciate the conditions under which its agents operate. Rigid organizational structure, poor access to recent information and useful extension materials, and adherence to outdated and unrealistic recommendations are three factors that greatly reduce the effectiveness of formal agricultural structure (Merrill-Sands and Kalmowitz 1990). Too often, extension content is fed to frontline extension agents through their supervisors in a top-down manner that discourages iterative, site-specific problem solving and precludes needed feedback. Most extension officers have no information materials to distribute to clients, holding on to the last copy of outdated brochures. They lack communication facilities or means of transportation. They have little or no budget and promised funds often arrive too late for planned field campaigns. Many extension agents pursue recent fads or are locked into jargon and frequently dismiss farmers for failing to adopt past ill-founded recommendations. Others insist that government officers must take the lead in all areas of collaboration and that other partners are only allowed to operate at their pleasure (Eicher 1999). Extension agents must be encouraged to integrate and reinterpret agricultural information rather than simply relay conventional knowledge (Mukhwana and Musioka 2003). But clearly, training extension agents in ISFM involves more than conveying new approaches to soil management, but also including them within a balanced, free-thinking collaborative framework where information flows, follow up actions are taken and outstanding performance is rewarded.

Many agricultural extension systems are well aware of their shortcomings and are taking important strides toward reform. Efforts directed toward re-training extension officers in the area of soil fertility should not only cover current techniques in nutrient management but also be consistent with these reforms by providing participating frontline extension staff with the diagnostic tools necessary for independent agricultural problem-solving (see Chapter 11). It is important that both extension agents and their supervisors participate in discussions intended toward improving their impacts upon the farming community. Many of the topics covered within this book are suitable for use in the retraining of agricultural extension agents in ISFM.

**Redirecting non-governmental organizations (NGOs).** NGOs have emerged as a powerful force for development in Africa because of their practical agendas and flexible operations. NGOs range in size from massive international humanitarian organizations to very small community focused operations. As the importance of ISFM grows within rural development agendas, more, larger NGOs will incorporate its principles into their development activities and numerous, smaller NGOs will likely form around it. Many smaller NGOs are committed to rural transformation and simultaneously undertake the many services necessary to stimulate economic development although skeptics challenge their expertise and endurance (White and Eicher 1999). Farm input supply is one of these actions and farmers may be provided with the improved seeds, mineral fertilizers and other products required to raise their yields to a target level (Denning *et al.* 2009; Gordon 2000). Often conditions are placed upon these recipients and the principles of ISFM can direct these organizations into devising a suite of farm activities that improve the effectiveness of delivered farm inputs. Examples of these conditions are that participating farmers collect and apply a recommended amount of organic inputs that complement mineral fertilizer addition (see Chapter 4), that water harvesting or soil conservation measures be installed within their fields (see Chapter 7) or legume intercropping or rotation be conducted (see Chapter 8) and some fraction of harvest be returned to the sponsoring organization for use as seed by others during the next season. It is important that international NGOs recruit experts in ISFM to design these programs.

Another common role of NGOs, regardless of their size, is the training of trainers. In the case of ISFM, this often involves the development of master farmer programs designed to stimulate farmer-to-farmer exchange in nutrient management and soil conservation. This approach was included by Sasakawa 2000 that has its extension workers trained at MSc. level at the University of Cape Coast in Ghana. Similar expertise through practical M.Sc. training has resulted from the Forum on Agricultural Resource Husbandry, a collaborative effort of Faculties of Agriculture in East and Southern Africa (Patel and Woomer 2000). About 16% of the FORUM's M.Sc. graduates in agriculture found employment with national NGOs, more than those entering universities, private enterprise or seeking higher degrees. These recent graduates working with NGOs were instantly networked with national public universities and their colleagues entering employment in other areas of agricultural research and rural development, particularly Ministries of Agriculture (Woomer 2003).

The key to farmers' problem solving rests in their own ability to diagnose and correct new problems as they arise. Farmers interact with, and seek assistance from other farmers and this situation provides an entry point for rural development (Patel *et al.* 2004; Woomer *et al.* 2003). NGOs often launch these programs by providing candidate farmers with the information and tools necessary to instruct others in different farm activities and enterprises and then providing each trainee with a modest budget for their activities. Ideally, community members benefiting from these services will subsidize and then fully cover these operations. Again, the poorest members of the community risk being bypassed by this pay for service approach unless a charitable component is included within its design and operating principles.

**Agro-dealer training.** Local dealers in agricultural inputs are not only well positioned to market farm input products to farmers but also to make useful recommendations on which of their products is needed and how it is best applied. In order to make best use of this opportunity, training of agro-dealers should be an integral part of a progressive capacity building program in

ISFM. The suite of necessary skills includes not only product handling and marketing, but also cost-effectiveness of alternative products, agro-enterprise development, applicator safety, combining field operations, recordkeeping and budgeting, and analysis of returns to investments by farmers. It is simplistic to imagine networks of farm input suppliers behave as trainers first and business persons second, but strong arguments can be formed around building trust between agro-input dealers and their customers. What is critical is for these dealers to know that getting involved in spreading ISFM knowledge to farmers is also an effective means of helping their business grow.

Training workshops may be specifically designed for farm input dealers that permits them to better stock soil fertility management products and to better advise client farmers about the product use. These novel workshops may be attended by over 50 agro-dealers that include two-day instructional sessions on ISFM and visits to diverse representative field demonstrations. A third day may be devoted to striga, pests and disease management and their relationship to soil fertility management. The field demonstrations are best situated across strong soil fertility gradients, allowing the diagnostic skills of participants to be sharpened. Individual participants should be asked to score different land management practices. Such an exercise is likely to reveal the following practical information; maize responds to fertilizer in most sites and differences between DAP and more expensive complete fertilizer blends are slight except where potassium becomes limiting, top-dressing of nitrogen is most effective following more complete fertilizer application at planting, differences in performance between recommended maize varieties of different commercial seed producers are slight when those varieties are properly targeted to representative agro-ecologies, and strong effects are observed in cereals following a legume rotation. Following a well designed workshop, agro-dealers become keenly interested in applying this information to future product orders and can better recommend these products, particularly when they are accompanied by written information (TSBF 2009).

**Professional and scientific training in ISFM**

We note with great concern the general trend of declining capacity in soil science and the slow pace of technical breakthroughs in ISFM. Soil science curricula within national public universities are too often out-of-date. Many national soil laboratories are deteriorating and admissions to soil science courses have fallen dramatically, even in countries with extreme dependence upon agriculture and its products. It is clear that an aggressive strategy is needed to reverse these trends and equip Africa's research and education systems with the human and physical resources required to support development, and better understand and sustain the agricultural resource base (Miguel and Kremer 2004).

Essential elements for building human and institutional capacity in soil fertility input recommendations in Africa need to target human resources, their interaction, communication, and the rehabilitation of physical resources (Swift and Shepherd 2007). Building human resources will require the identification of capacity building needs of the various stakeholders, develop curricula for university students on modern approaches for targeting soil fertility recommendations suited to African conditions, and provide short courses to farmers, extension officers and other stakeholders on fertilizer recommendation and development of user friendly information dissemination materials. To strengthen interaction and communication, there is a need to create platforms that allow scientists to develop research proposals, compare research results, identify general lessons, improve joint implementation of programs and projects across borders, by using and strengthening existing interactive and mutual-learning networks, and promote regular interactions with policymakers. There is also need to improve the physical resources by building series of well-equipped sub-regional or national laboratories and by re-equipping laboratories for the new ISFM agenda.

**Capacity building within universities and NARS.** Priorities for curriculum development include the upgrading of Diploma, BSc and MSc courses intended to prepare better extension workers and field technicians within rural development projects. Much of these contributions will be based upon the establishment of key field demonstrations and other best practice mechanisms that disseminate needed technologies to large numbers of farmers. M.Sc. and Ph.D. courses must prepare senior agronomists and soil scientists using advanced modules on modern soil science and agronomy including spatial decision support tools GIS, remote sensing, digital soil mapping, crop modeling, soil and plant analytical tools and diagnostic surveillance concepts.

Professional capacity building not just provides people with the skills and expertise to better accomplish tasks and solve problems, but should also enhance the scientific working environment so that individuals can exercise and further improve their capabilities. Over-generalized approaches to soil fertility improvement previously employed by many researchers are not appropriate within the context of ISFM. New methods and ways of conducting research that are more efficient are evolving. Effective implementation of ISFM requires that scientists have in-depth knowledge of their specific research discipline, as well as to broaden their scientific scope in order to be able to integrate the scientific work in other research areas, in social contexts, and to function in non-scientific arenas especially in dealing with other stakeholders such as smallhold farmers. Hence, the need for *T-shaped* skills, a concept that requires a well rooted multidisciplinary horizontal approach based on mutual understanding among scientists from different backgrounds, and a strong vertical range of skills in the area of soil fertility diagnosis and problem-solving.

In an effort to build a critical mass of such expertise in Africa, research networks are strengthened by conducting a series of short-term training courses to enhance these *T-shaped* skills of multi-disciplinary research teams (TSBF 2005). Courses designed for scientists already accomplished in soil fertility management cover topics including, but not limited to, participatory research and scaling-up, gender analysis, decision support systems, grantsmanship, scientific writing and presentation skills, soil conservation, carbon dynamics and sequestration and nutrient monitoring in agro-ecosystems. Other areas worthy of coverage include agro-enterprise development, commodity marketing, data management and statistical analysis. Such courses should target both the young and advanced professionals and participants from both universities and national research institutes in order to foster balanced skills in ISFM and continuity of career development.

ISFM must be better covered within national public universities and put mechanisms in place to review, update and rationalize curricula. For this reason, outside parties are advised to press their agendas upon universities in a manner that is consistent with curricula reform processes and not viewed as obtrusive by academic peers. In most cases, ISFM skills may be reinforced through existing undergraduate courses in crop and soil science. Soil microbiology courses should emphasize decomposition and nutrient mineralization of different quality organic materials, and the role of soil biota in land quality (Chapter 5). Instruction in soil fertility should emphasize the combined benefits of mineral and organic inputs (Chapter 1). Soil chemistry should emphasize the ameliorative influences of inorganic inputs and soil organic matter upon persistent constraints to crop production (Chapter 4). Soil physics should cover practical approaches to water harvesting and their role in enhanced soil productivity (Chapter 7). Crop science must include strategies of rotation and intercropping, including innovations relating to nutrient cycling (Chapter 8). These course updates are largely left to individual instructors and we hope the contents of this book will prove useful to them.

The creation of new courses and degree programs is more complex, usually requiring approval of university administrators and Faculty Senates. The topic of ISFM is well suited as a graduate-level course in Soil and Crop Science Departments and could benefit students pursuing careers in agricultural extension, teaching and research. Faculties that seek to launch such a course should consider the contents of this book as a structure for instruction in ISFM. While there is perhaps little need for special degree programs in Integrated Soil Fertility Management, clearly all Soil Science graduates should hold a developed understanding of the principles, practices and broader implications of ISFM and apply and advance this knowledge throughout their careers (Norman *et al.* 1994; Woomer and Patel 2000). One needed response by African universities is to establish an endowed chair on ISFM to ensure that this area of expertise is properly established within their institution's instruction, research and outreach activities.

**Laboratory rehabilitation.** The continent lacks adequate and well-equipped laboratories and staff that can offer precise and affordable soil and plant analysis services for the benefit of farmers. Conventional assessments of soil are somewhat expensive and there are frequently problems with quality control (Okalebo *et al.* 2002). It is important to upgrade at least one soil science laboratory in each country with modern equipment and methods. For example, all laboratories should have access to facilities for remote sensing and other GIS technologies, and new near infrared spectroscopic techniques that allow rapid, reliable and low-cost soil analysis. These laboratories should be inexpensive to equip and run, using mostly non-chemical approaches. Similarly, scientific and technical staff require on-the-job training in new approaches and methods.

The establishment of regional laboratories with more specialized equipment for advanced soil and plant analysis techniques, and resources for advanced GIS and database management could serve as reference laboratories and provide training and backstopping to the national laboratories. This centre is pivotal to upgrading both the physical and human capacity of African soil science. This center could consist of clusters of international and national research institutes and universities that promote integrated approaches. They would have state-of-the-art facilities including laboratories, equipment, databases, virtual libraries, training materials and distance learning built upon complimentary institutional advantages. Linking education and technical training with the research programmes of the centre of excellence will take advantage of the latter's physical facilities and expertise (Box 18.1). This problem-based approach to learning could build on existing networks of national and international research institutes. Internet communication among laboratories will become increasingly important for integrated data systems (Swift and Shepherd 2007). In general, the new soil science will increasingly demand strong skills in scientific method and quantification.

Finally, there is a need to build knowledge and skills in the area of linkages between soil science on one hand, and policy formulation and development strategies on the other. Capacity building efforts need to be targeted to both soil scientists and non-scientists in the wider development community. For example, soil scientists need training to communicate findings to different audiences, and to develop joint learning processes with policy makers, development partners and the private sector. These ideas are presented in greater detail in *An Investment Plan for Building Capacity in Soil Management in Africa* by Swift and Shepherd (2007) (Box 18.1).

**Farm organizations as the focus of capacity building in ISFM**

An important component of the development strategies of newly-independent African nations during the 1960s and 1970s was the establishment of agricultural cooperatives (Lynam and Blackie 1994). These organizations, designed to promote export of agricultural commodities such as coffee and tea, were directed through parastatal boards that were subject to political pressures and influences that did little to promote the welfare of small-scale farmers (Eicher 1999). The effect of this economic mismanagement was to breed strong distrust of government-controlled cooperatives among small-scale farmers. One condition imposed upon African nations during the 1980s and 1990s was that these monopolistic cooperatives be disbanded or privatized and that their input subsidy programs be discontinued (IFDC 2003; Smaling *et al.* 2006). The basis of these structural adjustments were often rooted in economic theory to

Box 18.1. Essential elements for invigorating educational and research capacities in African soil science (after Swift and Shepherd 2007)

**Human Resources**

- Identify core curricula for M.Sc. and M.Phil. courses and coordinate places of learning. These curricula should include topics such as knowledge management systems, encompassing a common monitoring and evaluation framework to synthesize results.
- Design Ph.D. fellowship programmes, sandwich programmes and research grant schemes.
- Build in multidisciplinary skills from B.Sc. level upwards.
- Promote post-doctoral fellowships and visiting scientist positions at the regional centres of excellence.
- Identify and support key universities for training in soil and land issues in each sub-region.
- Attach post-doctoral and other young scientists to centres of excellence.
- Provide scholarships with an emphasis on encouraging women soil scientists.
- Provide short courses and attachments to address specific needs, through local opportunities or training at advanced research institutions.

**Interaction and communication**

- Create platforms that allow scientists to develop research proposals, compare research results, identify general lessons and improve joint implementation of programmes and projects across borders, by using and strengthening existing interactive and mutual-learning networks.
- Include collaborative Ph.D.s with students from the north in project proposals
- Promote south–south and south–north collaboration of scientists through both short- and long-term exchanges.
- Promote regular interactions with policy makers.

**Physical resources**

- Build up a series of sub-regional laboratories by easing regulations on cross-border soil and plant movements.
- Re-equip laboratories in each sub-region for the new agenda (e.g. diagnosis, experimentation, soil molecular biology).

promote the role of the private sector and small-scale enterprise, but in reality, after the cooperatives were disbanded there was too few investors and entrepreneurs to fill the vacuum and agricultural services, including input supply and marketing. (Jayne *et al.* 2002; Omamo and Farrington 2004). Smallhold farmers felt abandoned by supporting institutions and justifiably so (Eicher 1999)!

Groups of neighboring farmers share common obstacles and opportunities and it is reasonable that they organize for collective action. The community-based organizations that arise commonly devote their efforts to accessing information, learning new technologies and pooling resources to acquire inputs or to market surpluses (Woomer *et al.* 2003). Most farmers, however, lack experience in forming self-help groups, particularly with the steps necessary to formalize and register their new organization. Part of the need for grassroots rural organizations throughout Africa is related to the weakness of formal extension services to the smallhold agricultural sector (Lynam and Blackie 1994). Many years previously, several programs were initiated in maize marketing, fertilizer supply and veterinary medicine but for a complex suite of causes, these services became scattered at best, and virtually non-existent for most (Eicher 1999). An abrupt introduction of market liberalization and structural adjustment imposed upon African nations by international donors and lending institutions was partly responsible for the removal of subsidies, but equally responsible was the lack of a new approach to equitable service provision that followed these changes in national policies. Yet, even farmers receiving the best extension services often find it in their common interest to form local organizations aimed at improving their individual farms and communities (Terrent and Poerbo 1986). Good farming involves intuition and skill but seldom close-held secrets. Indeed, the willingness of farmers to assist one another is a comforting feature of rural life.

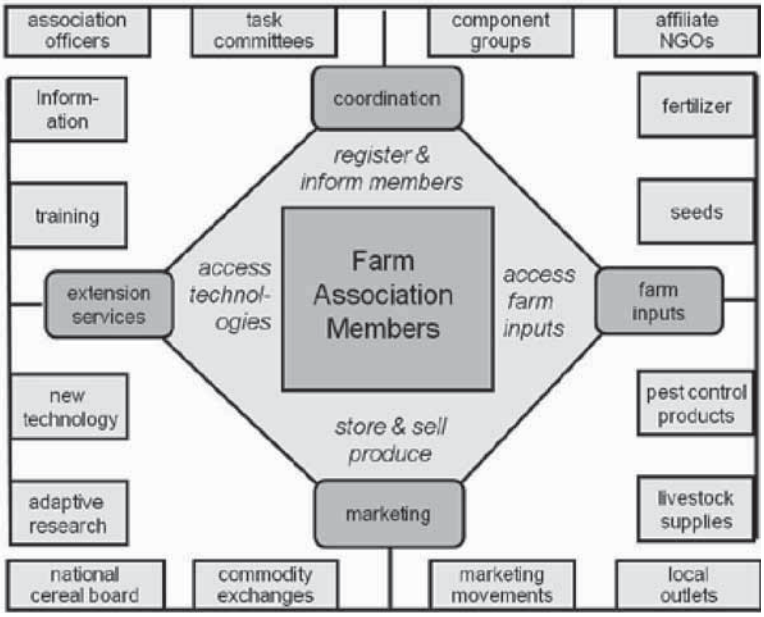



Figure 18.1. A conceptual model of empowering farmer association that offers information and extension services provides opportunity for bulk purchase of key farm inputs and is linked to top-end produce markets.

Organizing for collective action may be timely, but it also takes time. A large number of farmer self-help groups are emerging in Africa (Woomer *et al.* 2003), primarily to better access information and learn low-cost technologies. More recently, these grassroots organizations are consolidating into wider umbrella organizations in order to broaden the scope of their services. Stringfellow *et al.* (1997) recognize this kind of development as positive, but caution donors and development organizations from overburdening these newly-formed organizations with too complex or too many tasks. At the same time, the members of these new farmer associations are expecting services in return for the time and dues spent on them (Figure 18.1). Farmers that have joined these agricultural movements expect better access to and more reliable information, strengthened capacities for adaptive research, particularly in the areas of soil fertility management, pest and disease control, better access to, and lower costs for key agricultural inputs, particularly improved seed and fertilizers and improved access to higher-end buyers to market their crop surpluses. Furthermore, these four arms of empowering farmer associations (Figure 18.1) are not independent of one another, but rather represent an orderly progression in first, understanding and mobilizing land management technologies, and then using them to raise farm productivity beyond smallhold subsistence. Farmers and their organizations must not be viewed as passive targets for ISFM messages but rather as willing partners in their refinement. All capacity building actions must take into account the provision of broader services, particularly farmers' improved access to technologies, farm inputs and commodity markets, and their expectations of improved living standards as these are the reasons farm organizations are formed in the first place.

**Integrating capacities in ISFM**

Capacity building in ISFM involves more than educating or re-educating individual stakeholder groups but it also implies a re-orientation of conventional approaches to soil fertility management, the development of new sets of skills and the re-tooling of soil laboratories. In short, ISFM requires interdisciplinary thinking that encompasses a range of stakeholders. ISFM planners must consider development projects that cover multiple scales from fields through farms, communities and watersheds to nations and regional bodies. In this way, capacity building begins with farm households and extends to rural development specialists and policymakers that are presumably working on behalf of the agricultural community. Policymakers require general knowledge and recent information on soil management as well, and this topic is considered in the Chapter 19.

New approaches to soil fertility management do not require that different actors become experts in all fields; rather, they must become better prepared to participate within interdisciplinary settings and to constructively interact with experts from other fields. This situation is particularly true for soil scientists that, despite skills in scientific and field approaches leading to important findings, too often find it difficult to explain their discoveries to others or translate knowledge into practical collective action. ISFM involves more than a suite of land management principles and their accompanying technologies, but also the knowledge of how to apply these and the larger environmental and social issues related to better land stewardship. Soil nutrient depletion resulting from continuous cultivation by smallholders presents a huge challenge to African agriculture and regional food security (Smaling *et al.* 1997) and capacity building in ISFM must reinforce the broader importance of responsible land management. The same may be said for watershed protection and greenhouse gas mitigation. Civic accountability and ethics also have an important role in capacity building. Leaders within the rural community must set positive examples for others by adopting and promoting needed technologies and new enterprises even though their livelihood may not be as at risk as less affluent households. Officials of farm organizations must be transparent in their relations with co-operators and members alike, and agro-dealers must not mislead customers in their pursuit of greater profits. ISFM empowers farming households to wiser decisions concerning crop enterprise and resource management on a daily basis and this more holistic view of ISFM must also be portrayed in capacity building as well.

# Chapter 19. ISFM in the policy arena

A major factor that limits widespread adoption of ISFM is lack of innovative and bold policies addressing necessary facets for its promotion. Government policy should ensure that farm input manufacturers and suppliers, farmers, commodity buyers and processors, and development agents form strategic alliances and work together in mutually beneficial manner. The capacities of different actors must be strengthened for effective participation and contribution in public meetings geared at making informed input into ISFM policy formulation. All issues that constrain smallhold farmers' access to farm inputs and commodity markets such as unstable prices, high cost of transport, lack of standard measures, irregular quality control, and development of effective producer organizations for increased bargaining power must be addressed. Other issues that bear on adoption and retention of ISFM such as subsidies, credit and loans, and effective workable contract laws are also important to mainstreaming ISFM.

Very little progress has been made on elevating the importance of soil fertility issues. For instance, national soil fertility strategies have been developed in a few sub-Sahara African countries but with strong external influence and much focus on the role that mineral fertilizer could play. In fact, such strategies have been drafted in countries such as Burkina Faso. However, due to lack of public funds, the national assembly of most countries has not approved most of such strategies. High level lobbying of key stakeholders (including national governments and donors), championed by technocrats in the area of agricultural resource management and related disciplines, is necessary to move these drafts to the next level. Although it has taken long, policymakers are finally acknowledging the potential roles of organic resources and ISFM. New fertilizer strategies, where the science of ISFM plays a critical role, are being designed following the African Heads of State and Government Fertilizer Summit held in Abuja, Nigeria in June 2006 (Africa Fertilizer Summit 2006).

Reliance on traditional agricultural extension approaches and subsequent farmer-to-farmer diffusion is successful in dissemination and uptake of technologies when the technologies are less knowledge intensive and do not require overly complex adaptation to local farming conditions (Giller 2002; Vanlauwe *et al.* 2006; Woomer *et al.* 1999). Successful promotion and adoption of legume-cereal rotations required little more than new grain legume varieties becoming available and the distribution of accompanying agricultural extension messages (Mpepereki *et al.* 2000; Sanginga *et al.* 2003). Because of the complexity of ISFM technologies in other settings, however, there is need to support its wider understanding and adoption through specialized agricultural extension policies. Such specialized policy-led agricultural extension programs such as the Starter Pack and subsequent Targeted Input Program in Malawi resulted to a large payoff even in the face of a huge implementation cost (Blackie and Mann 2005; Denning *et al.* 2009). Insights gained with the Starter Pack program show that targeting inputs provides a vehicle for rapidly and widely disseminating technologies that permitted farmers to access fertilizer and other farm inputs (Levy and Barahona 2001). For simple farm technologies such as fertilizer and seeds, market-led extension approaches remain the most effective approach to agricultural development, especially in places where land managers are readily able to access and afford the required farm inputs, but for more complex technologies or difficult developmental settings, additional carefully formulated enabling policies are required.

### ISFM policy realms

For effective and efficient ISFM policy formulation and implementation, it is important to structure the existing policies in terms of their target, compliance, enforcement and impact. Given the current level of knowledge, ISFM-related policies could be classified into five groups.

**Beneficial policies or by-laws reinforcing ISFM that are not being followed or enforced.** An example is the prohibition of the burning of crop residues in Kenya. This similarly applies to conservation polices or by-laws which are meant to enhance environmental protection. A review of policy and by-laws relating to land management and conservation in Africa indicate that many measures were potentially useful but were ineffectively implemented because responsible institutions were weak or poorly organized (Eicher 1999). In order to enjoy the benefits from sound ISFM such policies must be enforced.

**Policies which are inimical to widespread adoption of ISFM technologies.** This situation when policies create unnecessary obstacles between technology providers and their intended beneficiaries. Prohibition of fertilizer and seed repackaging as a means of protecting consumers exists in many countries but these regulations in effect prevent local input suppliers from marketing materials in the smaller quantities demanded by their clients. Such ISFM policies must be revised or repealed. Other examples include prohibition of intercropping in Rwanda that prevents farmers from deriving the numerous benefits of multiple cropping, and the prohibition of the selling of maize outside of specified administrative areas in Malawi which deprives farmers' access to higher prices elsewhere.

**Policies that offer incentives to the intended beneficiaries.** Such policies often favor input-output market linkages and increased returns to ISFM practices and must be retained, nurtured, and further promoted for widespread and increased impact. Examples include policies that secure property rights, enable farmers to hold service providers more accountable, enhance training and capacity building at all levels, and measures that strengthen farmers' bargaining power in otherwise one-sided farmer-industry relationships. Policies towards sustainable land use intensification and the necessary institutions and mechanisms to implement and evaluate its benefits also facilitate the uptake of ISFM. Other interventions include policies related to importation of fertilizer and agro-minerals, blending and packaging of fertilizer, or smart fertilizer subsidies needed to provide timely access to sufficient fertilizer at reasonable prices (Denning *et al.* 2009; Sanchez 2009). Specific policies addressing the rehabilitation of degraded, non-responsive soils may also be required since investments to achieve this may be too large to be supported by individual farm households alone (Buresh *et al.* 1997).

**Policies with positive and negative impact on ISFM depending upon how they are interpreted or implemented.** Policy change following the Structural Adjustment Programs of the 1980s and 1990s heavily and non-selectively reduced government agricultural support. Other examples include policies requiring excessive information on seed and fertilizer packages and measures that impede the right to form farmer associations. Although, prohibition of repacking of inputs helps check adulteration, it reduces widespread access to inputs, especially where farm input manufacturers and distributors are not keen on producing the smaller packages affordable to poorer farmers (Blackie and Albright 2005; Woomer *et al.* 1997). In addition, farmers' right to form grassroots and larger associations is necessary to achieving larger rural development goals (Chirwa *et al.* 2005; Stringfellow *et al.* 1997) but including any but token registration fees poses an unnecessary constraint to grassroots membership, especially among the poorest households that stand to benefit most from participation (Woomer *et al.* 2003). Policies that support the traditional rights to free grazing in situations where establishment of land tenure and increasing land use intensification support adoption of ISFM are also counterproductive.

**Policy vacuums that impede ISFM.** One example is the lack of tenure security in Ethiopia, Tanzania and many other sub-Saharan African countries, a situation that had strongly discouraged tree planting that in turn results in widespread use of livestock manure and even crop root residues as cooking fuel rather than soil inputs. Similarly, the lack of investment in information and knowledge systems, particularly support for national agricultural extension service, inhibits the training in knowledge intensive ISFM technologies. Added to this is the fact that national soil fertility maintenance strategies exist in only few countries in sub-Saharan Africa. However, it is important to note that in many sub-Saharan African countries, property rights are not constraining. For instance, despite policies that are mixed in terms of property rights, farmers in Nigeria continue to make long-term investments in agroforestry technologies (Adesina and Chianu 2002). Another clear case of a policy vacuum is the continuing land fragmentation even to uneconomic levels due to inheritance and continuous land subdivision from generation to generation. The problem of this lack of policy for land consolidation is compounded by-laws that prevent landowners from selling or consolidating their land holding without permission from government authorities.

### Economic incentives for ISFM

Economic incentives are important for widespread adoption of ISFM technologies and policies are critical for creating and backstopping those economic incentives. Conversely, inadequate agricultural policies and lack of economic incentives such as poor farm produce prices, lack of crop and livestock insurance, poor transportation and communication infrastructure and failure in promoting agricultural exports hamper investment in soil fertility maintenance that in turn reduces land productivity. In China, improved rural roads network was a stimulus for agricultural technologies. Too often, markets for mineral fertilizers are weak including credit mechanisms for timely purchase and application of farm inputs. Government investment in large-scale conservation or irrigation projects also reduce the social returns to ISFM.

Many smallhold farmers have limited ability to enter markets because they operate in remote areas. Effective policymaking for promoting ISFM technologies depends upon agricultural transformation that permits these farmers fuller access to farm input supply markets as customers and commodity markets as producers. Active farmer associations must become established and provide members with essential services (see Chapter 18). Policy-oriented market research and knowledge systems for ISFM involve identification of strategies that improve incentives to invest in emerging market enterprises by literally millions of poor farm households throughout sub-Saharan Africa. Policy and regulations are critical for viable farmer input-output market linkages and enhanced returns to ISFM. Market linkages support ISFM because it is practiced more where farmers have access to farm inputs, credit facilities, storage facilities, and fair produce markets.

Translating ISFM into impacts require effective policies and regulations concerning credit, subsidy and input-output market development, as well as establishing stakeholder dialogue, communications, and even lobbying. For instance, smart subsidies can greatly stimulate farmer investment in the use of mineral fertilizers and improved cereal seed, which in turn results in food surpluses where in the past food security was tenuous (Denning 2009). Although market-led agricultural extension is not yet widely practiced in Africa, it has the advantage of linking input supplies to financial markets and commodity buyers in a way that can provide smallhold farmers with incentives to further invest in ISFM.

Another area requiring attention is the regulation of farm input packaging and repackaging with strong penalties to ensure quality and prevent adulteration. Concerns over seed quality and type can inhibit its sales. Such problems require an infusion of trust into the market, which could be done through farmers' associations. For an association, there is initial need to help them get off the ground through marketing their services. At community scale, there can be need to train on how to collect, store, package and test.

Outgrower schemes are an important means of achieving linkages between farm inputs and guaranteed commodity markets. Many of the schemes supply fertilizer, seeds and other inputs to farmers on credit in return for signed contracts agreeing to produce and deliver a certain commodity. These have been found to work very well in Africa for higher-value products, particularly export crops such as tea, coffee, vegetables, fruits and cotton. It has not been found, however, to perform well among producers of staple crops due in part to their lower values and also because of the large number of buyers and sellers involved. Credit schemes are very rare for smallholder agriculture outside of these outgrower schemes. Appropriate policy formulation, therefore, needs to be carried out to direct greater investment toward the producers of staple crops in Africa.

**Support services and platforms for ISFM**

In much of Africa, agricultural support services such as government agricultural extension systems are weak. Much of the innovation in agricultural extension has been performed by NGOs with small and less trained staff. Little progress has been made on technical support and grain legume seed systems. For instance, farmer field schools have been spreading slowly. Agricultural research institutions are poorly funded. One of the immediate results with direct relevance to ISFM is the systematic reduction of soil science capacity throughout Africa. Policies are critically required to reverse these ugly and agricultural productivity-threatening trends.

There are however opportunities to influence national-level and regional level policies in many SSA countries, taking advantage of current reforms and political engagement related to the Abuja Declaration and other agricultural development initiatives such as those of the World Bank, the International Fund for Agricultural Development (IFAD), and the African Development Bank (AfDB). Advantage should also be taken of the current reforms and political engagement to strengthen and promote policies that favor input-output linkages for enhanced returns to investment in ISFM. Examples of such good policies should include those that address the problems of access to appropriate farm inputs necessary for farmer adoption and retention of ISFM practices, enhance ISFM-related knowledge creation and information dissemination, and create tax incentives for increased and widespread adoption of ISFM practices. Further, policy support is required for agro-dealers, micro-finance agencies, and other actors in the private sector for ISFM-related input-output services, farmers' associations for effective ISFM input-output service provision to members and rural value adding enterprises that increase farmers' net returns and prolong the shelf-life of agricultural produce. Policies that ensure long-term adoption of the best practices of ISFM by smallhold farmers could counteract the massive negative nutrient balance that is commonly observed in SSA (Smaling *et al.* 1997). Platforms to facilitate related ISFM policy interactions at national and regional levels must be established. Need exist to harmonize relevant ISFM-enhancing sub-regional, regional, and continental policies and regulations. Some of these could involve the removal of cross boundary barriers. Alternative mechanisms for viable research-to-policy platforms must identified.

**Key elements of ISFM policies**

Important policy elements include accountability, implementation plans, institutional support and participatory community-based extension. Others considerations are involvement of agro-input dealers' network, integration of ISFM into development agendas and capacity building, seed and fertilizer strategies, and complementary investments. These should lead to the formulation of sustainable and effective ISFM policies.

Accountability entails the development of ISFM policies whose mechanisms build in answerability to target beneficiaries. The implementation plans for the stated ISFM policies must be clearly indicated. Some of the past soil fertility management initiatives failed due to lack of adequate policy and institutional support. The absence of policy support at national and regional levels has been a critical missing element that forestalled the achievement of the impact of ISFM technologies at scale in the past. Lack of funds also contributed immensely to the problem.

Although policy support is critical for widespread and accelerated adoption of ISFM, most of the existing agricultural development policies in SSA were not fashioned with 'complete ISFM' promotion in mind (see Chapter 1). While some of the existing policies support and enable components of ISFM, others are completely inimical to widespread ISFM adoption. Basic up-scaling of good ISFM practices requires effective policy and institutional support, especially given the devastating effect of the structural adjustment program of the 1980s and early 1990s that dealt a blow to the formal agricultural extension programs of most Ministries of Agriculture in Africa. The associated job cuts and downsizing disproportionately affected the Ministry of Agriculture in most countries.

**Innovative agricultural extension.** There are examples of policy-led extension such as the Starter Pack and Targeted Input Program in Malawi. Although, massive funds were used in the dissemination of this intervention, the result was very encouraging. However, repeated failure of conventional approaches to technology dissemination elsewhere has led to experimentation with more participatory methods. There is now a large body of literature that indicates that farmer participatory research is vital for re-orienting smallholder farming systems (Johnson *et al.* 2003; Pound *et al.* 2003). One community-based agricultural extension program is the Farmer Field School (FFS) approach. While FFS appear to have reduced effect upon persistent transmission of knowledge among farmers (Tripp *et al.* 2005), however, FFS networks in Africa demonstrate a trend towards organizing for market engagement. There are contradictory findings on whether FFS is a cost-effective approach to technology dissemination and adoption (Feder *et al.* 2004). Many other approaches exist and are being tested by various research institutions, especially given the involvement of a diversity of NGOs (see Chapter 13). Generally, there are only slight differences in their approach to technology dissemination, awareness creation and target client training. Stronger aspects of FFS must be capitalized upon with new elements added to address their shortcomings.

**Integrating ISFM into development agendas and capacity building.** Strategies are required that effectively integrate ISFM into national and regional fertilizer promotion, agricultural development and poverty reduction efforts. This intervention option would establish mechanisms for capacity building, institutional learning, policy dialogue and advocacy at different levels to bring about policy and institutional reforms favoring all stakeholders, especially the rural poor. It is important to review national agricultural development strategies to identify gaps in policy that will favor the adoption of ISFM, then suggest alternative policies addressing above gaps and finally build capacity of all, including institutions, involved in policy making for informed agricultural development. The poverty reduction strategy of Rwanda incorporate soil fertility improvement issues. Most African other countries lack policy instrument. Increased efforts must be directed towards integrating ISFM into major agricultural development initiatives and sustainable land management programs in SSA (e.g., Comprehensive Africa Agriculture Development Programme of the New Partnership for African Development – CAADP-NEPAD,) and in the development agendas of international NGOs. Through the New Partnership for Africa's Development (NEPAD), CAADP addresses policy and capacity issues across the entire agricultural sector and African continent, is entirely African-led and represents its leaders' collective vision for agriculture in Africa. Overall, CAADP's goal is to eliminate hunger and reduce poverty through agriculture. To do this, African governments have agreed to increase public investment in agriculture by a minimum of 10 percent of their national budgets and to raise annual agricultural productivity by at least 6 percent by 2015.

**Seed and fertilizer strategies for ISFM.** Effective seed systems (especially for grain legumes) are critical for accelerated and widespread adoption of ISFM. Strategies must be developed for it, especially given the limited interest of the commercial seed sector in grain legumes. There is a strong need to pay due policy attention to all these components to incrementally attain the benefits of 'complete ISFM' (see Chapter 1). In particular, there is the need to facilitate and promote seed associations and community seed production.

**Complementary investments.** Strategies should be developed to effectively link and coordinate input-output markets related to ISFM. The lack of coordination in input-output markets means that programs focusing on either input or output marketing alone often fail as a result of the absence of complementary investments in related aspects of the supply chain. Coordination of the supply chain contributed to the success of the soybean-maize rotation ISFM in Nigeria, Zimbabwe, and Kenya, to mention a few African countries.

One of the key challenges that constrain the adoption of even proven technologies in SSA is the lack of platforms linking actors along the research-development-policy continuum. This poses challenge that faces both policymakers and private sector ISFM stakeholders. Also the links of improved soil fertility to environmental services need to properly permeate policy and development programs, and to reach out toward emerging issues such as developments in carbon markets intending to ameliorate global climate change.

# Chapter 20. Marketing support for ISFM

The adoption, retention and sustainable impacts of ISFM depend upon the extent to which it is profitable and fits into farming systems. Strengthening and increasing market opportunities for small-scale farmers and linking input-output markets constitutes one of the potential routes out of poverty in SSA and provides great opportunities for smallhold farmers and other interests along the production-to-consumption chain. In this way, it has the potential to reduce the risk of leaving small-scale African farmers behind as occurred with the earlier Green Revolution (Okigbo 1990; Hazell 2005). Linkages that allow farmers to simultaneously and reliably access a range of resources, services, and commodity buyers are critical if they are to survive in an increasingly competitive agricultural food market (Poulton *et al.* 2005).

Much needs to be done to stimulate the profitable adoption of farm inputs, particularly among resource-poor farmers (Crawford *et al.* 2003) and calls for policy on linking input-output markets. Place *et al.* (2003) note that there is no direct evidence of the effect of the use of ISFM on markets for fertilizer and seed. Their analysis of indirect evidence, however, suggests that this link is potentially important. Although seeking to raise yields and outputs in small-farm agriculture is valid in contemporary poverty reduction strategies in SSA (Ellis 2005), this strategy is unlikely to be sustainable if input and output markets are not linked, creating difficulties for farmers who may not be able to sell their produce surpluses. This shows how raising yields and outputs cannot single-handedly provide the engine for poverty reduction in SSA (Ellis 2005). Improved supply of farm inputs and reliable produce marketing help create well functioning marketing services that stimulate production through better crop and soil management (Lerman 2001).

### Access to market, technology adoption and poverty reduction

Success in transforming African agriculture must address the challenges faced by millions of smallhold farmers. This is particularly important if the strategy of introducing ISFM technologies is to lead to better farm income and improved wellbeing for rural households. Wider uptake of improved agricultural technologies is often inhibited by lack of the necessary pre-conditions for surplus production and sales.

Sustaining success in agricultural growth and adoption of ISFM technologies presented throughout this book critically depends on expansion of farm input, financial and produce markets (Reardon *et al.* 1997; Diao and Hazell 2004; Bingen *et al.* 2003). The level of farmers' market orientation underlies their willingness and ability to pay for farm services (Omore *et al.* 1997). Better access to profitable markets leads to crop intensification, investments in natural resources management, and adoption of improved agricultural technologies (Tiffen *et al.* 1994). However, it has been difficult to reach agreement on what should be done to improve the performance of agricultural markets in SSA (Poulton *et al.* 2006). Efforts must be made to increase the attractiveness of agricultural commercialization and make it beneficial to all involved, especially small-scale farmers. One major bottleneck in current marketing approaches is the compartmentalization and lack of coordination of input and output market promotion and the tendency to market farm inputs in quantities most farmers cannot readily afford. The types of coordination needed are vertical coordination to address problems of specific assets, risks, thin markets, product quality and timing, and missing credit markets; horizontal coordination that addresses problems of public goods such as research and extension, credit, grading, and staff development; and complementary coordination to address problems of service delivery and access in least developed settings (Figure 20.1).

**Alternative marketing arrangements**

Examples of alternative input-output marketing arrangements include contract farming, out-grower schemes, farmer cooperatives and associations, agro-dealer networks, and commodity exchange platforms. These mechanisms have a potential role to play in improving and driving market development in SSA and have done so in the past with varying degrees of success (Dorward *et al.* 1998). Under some contract farming arrangements, agribusiness firms provide farmers with inputs, extension advice, and commodity marketing services in exchange for commitment to supply their produce at an agreed upon price (Stockbridge *et al.* 2003). Limited market information systems and lack of effective linkage between input-output markets have attenuated the usefulness of the alternative marketing arrangements. For example, agribusinesses usually have better information and marketing strength compared to smallhold farmers and this advantage may carry over to contract negotiations.

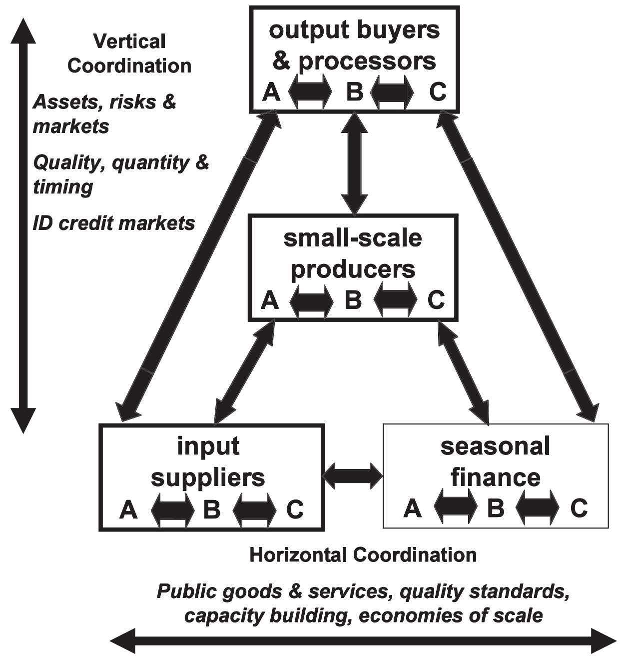



Figure 20.1. Vertical and horizontal coordination needed to address marketing bottlenecks.

More efficient commercialization and marketing of farm inputs are often emphasized within rural development initiatives in sub-Saharan Africa (TSBF 2009). Several development organizations and their donors now recognize that technical advances in soil fertility management are realized at the farm and community levels through the availability of products marketed by agro-dealers (CNFA 2002). Important questions concerning the accessibility of markets for surplus crop production resulting from greater use of farm inputs are now being considered within the context of farm technology dissemination strategies. Benefits of marketing initiatives must extend beyond the agro-dealers themselves and their resource-endowed clients, and specific activities designed to include poorer households. In some cases, the poorest rural communities face huge barriers to market participation that include lack of market information, inadequate transportation, insufficient bargaining power and credit facilities, and non-existent or weak farmer organizations. Thus, factors not directly related to land management practice still result in restricted dissemination of ISFM. However, the marketing interventions offered by these development agents may be seen as a transient phase during which expansion of rural trader capacity can lead to more competition among buyers and emergence of a more responsive service sector. The value of crop response to input use increases only when converted to cash income through marketing, and when such investment provides higher returns to farmers.

**Bottlenecks to market development**

Compartmentalization and lack of coordination between farm input and produce markets are among the major bottlenecks in SSA. In the past, programs focusing on either farm inputs or commodity marketing alone often failed due to lack of complementary investments in the other. Some programs designed to promote farm inputs but not commodity markets have proven successful from the standpoint of increasing farm production including the activities of CNFA (2002), IFDC (2002), Agricultural Market Development Trust (AGMARK), Sasakawa-Global

2000, and the Farm Inputs Promotion Services (Blackie and Albright 2005). At the same time, there are also examples of fertilizer and seed promotion that led to productivity growth but depressed local output prices (Crawford *et al.* 2003), demonstrating how market failures can counteract benefits of productivity growth and discourage investments. The experience of Sasakawa-Global 2000 in Ethiopia that promoted fertilizer use on maize production with little or no attention to output markets is one of the failures of compartmentalized approaches because input use resulted in depressed output prices (Crawford *et al.* 2003). There are indications that the current situation of good maize harvests resulting from fertilizer subsidies in Malawi described by Denning *et al.* (2009) may in fact lead to falling prices, leaving farmers stranded as government prohibits the sale of maize outside the country and is not prepared to purchase it or offer price guarantees. ISFM promotion must emphasize the need for both farm input supply and commodity markets as included in the approaches pioneered within the Millenium Villages (Sanchez *et al.* 2007). As a result of these experiences, several other initiatives across SSA are now seeking to simultaneously link farmers to both farm input technologies and produce markets.

Organizations focusing on output markets such as the Sustainable Agriculture Center for Research, Extension and Development in Africa (SACRED-Africa), Farmers' Own Trading Limited (FOTL) and Techno Serve did not address input markets, a situation that leads to low returns to land and labor and discouraging farmers from further production (Mukhwana 2000). Others explore both input and output markets as international consultants, however their terms of reference often lack the level of coordination required for comprehensive and well coordinated market development.

Compartmentalization leads to low access to inputs, limited access to output markets, market failures (Ellis 2005) and constitutes uneconomic and unsustainable approach to balanced market promotion in SSA. Under compartmentalized marketing, feedback on effects of ISFM by farmers and its effect on their livelihoods is not considered. Broader approaches identify cost-effective ways of increasing access to inputs, improve input delivery, and link farmers to output market to earn income to pay for inputs and attend to other household needs. Integrated rather than compartmentalized input-output marketing is needed to effectively deal with more demanding marketing chains. The advantage for smallholders to produce crop surpluses can only be realized once traders move into rural areas to purchase commodities from growing rural markets, yet this market linkage is slow to develop, in large part because of massive food importation. Nonetheless, optimism is growing towards potential African staple food markets (Hazell 2005).

It is also crucial to identify and remove factors that have perpetuated compartmentalization and reach a situation where farm input use and produce sales become parts of a chain, raising productivity and income, protecting the land, and distributing safer, more nutritious food. In few instances, this is presently happening at farmers' organization level where marketing services are provided to members (Stockbridge *et al.* 2003). Nonetheless, lack of empowerment of smallholders on how to effectively tackle output marketing in the face of limited infrastructure accounts for limited success in this direction. Too often, donors also place unbalanced emphasis on input market development. The production-oriented bias of Africa's Poverty Reduction Strategy Papers (Ellis 2005) seems to give credence to compartmentalization by paying more attention to farm inputs, rather than outputs.

**Case Study: The rise and fall of Western Kenya's Maize Marketing Movement**

The Maize Marketing Movement (MMM) was initiated in September 2002 to design and test a prototype system for storage, bulking and marketing of maize by poor farmers in western Kenya, thereby improving their market access and incomes (Woomer 2002). Its approach was modeled upon the experiences in West African cereal banking (Graham 1991; von Davidson and Loy 2001). The general approach undertaken by the lead NGO, SACRED-Africa, was to invite farmers surrounding five trading centers to participate in cereal banking and to assist interested parties in formalizing these groups (Mukhwana 2000). Each local cereal bank was required to register its members, elect officials and establish a bank account. The lead NGO provided on-site training to 333 MMM members in post-harvest handling, storage pests and quality control. The NGO also provided specialized training to the 15 elected officials from the five branches in civics, bookkeeping, sales, and marketing. Each marketing branch next established a maize storage and market information center, installed maize processing equipment and received a loan enabling them to begin trading maize.

The lead NGO also established the MMM Central Cereal Bank near its headquarters in Bungoma town. This facility included a grain quality laboratory that provided services to the local marketing branches and a 250 t storage facility located along the railway to Nairobi. The larger grain borer (*Dinoderus trunchatus*) had recently invaded Western Kenya and protocols were established that allowed for its control through chemical dusting. Later, NGO staff became certified as phosphene fumigators to more-effectively control borer outbreaks within storage facilities. Project staff also developed guidelines and distributed tools that allow for maize to comply with national standards for moisture content (<13.5%), diseased (<3%), insect damaged (<3%) broken (2%) and off-color (1%) grains, and foreign matter (<1%). Once quality control standards among the MMM members were assured, the project started to bulk and trade maize within 10 months after initiation of the project.

Over the next 14 months (October 2003 to December 2004), the MMM sold over 560 t of top-grade maize for $108,000 and held an additional 67 tons of bagged maize in reserve. Unga Millers, Kenya's largest processor of maize meal, accounted for the majority of these sales, purchasing 393 t of maize in three shipments (Figure 20.2). This marketing strategy generated an additional $17,400 compared to marketing through the nearby National Cereal Producers Board, and an extra $41,400 than had these farmers sold at the farm gate to local assemblers. Maize was also directly marketed to members of the public during the hunger season and to local schools and other institutions (127 tons), greatly improving community food security. The MMM developed a reputation among buyers as suppliers of premium quality maize and demonstrated its credibility to its members and their neighbors. In many cases, the movement brought newfound vitality to its trading centers and collection points by providing marketing opportunities and part-

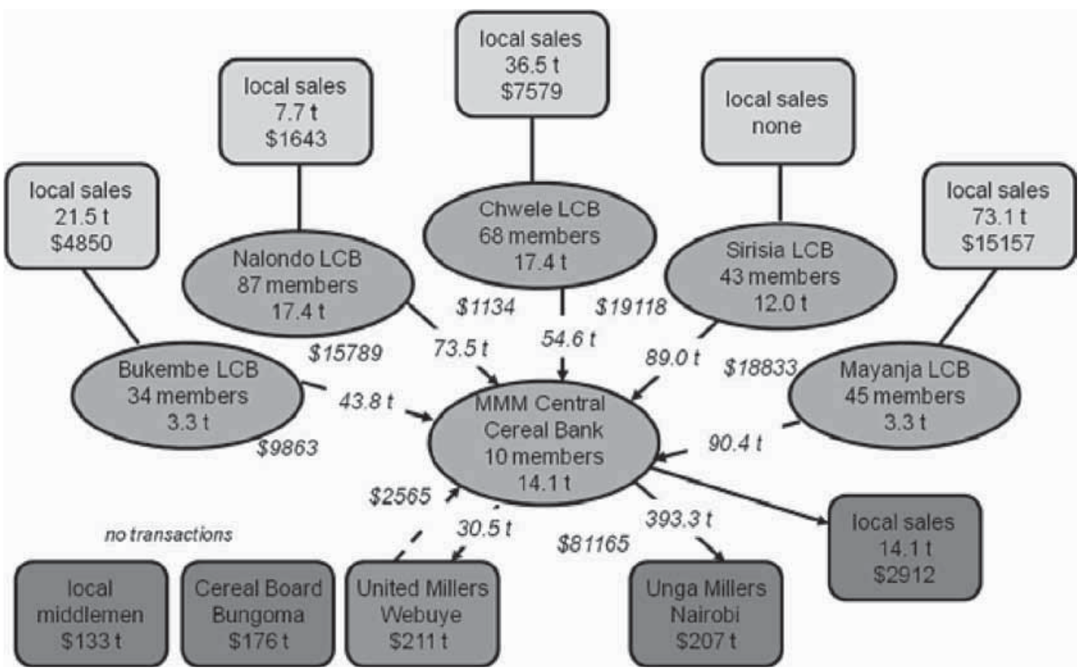



Figure 20.2. Maize trading by the Maize Marketing Movement and its component cereal banks between October 2003 and September 2004.

time employment to many households.

MMM suddenly became a donor's success story. Hosting delegations from several development organizations became almost a routine. Kenyan government officials recognized the project and sought to establish local cereal banks in their constituencies. Based upon these early successes, an expansion of the MMM was launched that brought operations to three nearby administrative districts creating 20 additional local cereal banks. Buoyed by their success, SACRED-Africa moved its headquarters 420 km away to Nairobi for greater donor exposure. Unfortunately, early signs that the MMM was being prematurely sensationalized were ignored including few follow up maize deposits by members, economic losses reported by local cereal banks due to inexperience and excessive costs, poor documentation of local sales, reduced quality monitoring, no further improvement in processing tools and a decline in cereal bank membership.

Project managers had become over-confident and distracted from their work plans, too involved with outside training and consultancies and locked into quasi-profitable maize trading ventures rather than exploring innovative marketing opportunities as originally intended. These distractions resulted in no large collective sales following the next season that in turn led to excessive ad hoc trading by local cereal banks and accompanying irregularities in financial control. Misdirected revenues by local bank officers resulted in net losses and inability to repay project loans. A FAO-World Bank team conducted an unscheduled visit in May 2005 that led to an unfavorable project evaluation. In response to declining project performance, skilled staff members grew demoralized and resigned without attempting to diagnose underlying causes of shortcomings, resulting in additional, uncompleted project milestones including needed improvement of grain processing tools and the production of a training video and booklet. Based upon these weaknesses, the donor withdrew its planned support for the expanded project.

The MMM was originally intended to serve as an exploratory pilot project yet it was later unfairly discredited as a non-viable business venture. Plans were made by members to continue the cereal banks without donor support, placing local banks under greater supervision, imposing additional service fees to cover expenses and halting trading in non-member grain. Unfortunately, premature withdrawal of donor support caused the faltering cereal banks to collapse over the next few growing seasons. Nonetheless, several valuable lessons emerged from this courageous collective marketing effort.

Smallholds were not too small to be economically viable as maize and legume producers. Indeed, participating smallholders were quickly organized for collective action after receiving basic training in cereal processing and being provided a convenient collection point to deposit their crop surpluses. In the moderate to higher potential agricultural zones of Kenya, household food security may be achieved by employing ISFM technologies on relatively small land areas that better position small-scale farmers to produce crop surpluses. Take for example, the adoption of staggered ISFM maize-legume intercropping (Woomer 2007). A family of eight requires approximately 1000 kg of grain per year. Given current maize-bean intercrop yields in absence of inputs, this yield is achieved by intercropping on 0.38 ha twice per year (Figure 20.3). Through ISFM in a bimodal precipitation regime, food security is achieved through double cropping 0.14 ha, requiring only $9.10 of additional investment in fertilizer and improved seeds. Viewed in another way, intercrop yields may be increased by 1500 kg $ha^{-1}$, worth $222 when improved intercropping is employed on the 0.38 ha previously required to meet household needs for an additional cost of only $26.

Smallholders produced grain that met the quality standards of top-end buyers (see table 14.1). Many smallholders are currently unaware of established quality control standards and how o avoid jeopardizing that quality during grain processing. This situation is another reflection upon poor market intelligence by farmers who, in the past relied upon government bodies to test and either accept or reject their maize through, what was to them, a rather cryptic process. The experience of the MMM indicates that grain quality immediately improves after farmers are introduced to the concept of quality control protection through on-site training, and later provided with basic processing tools through their local cereal banks (Mukhwana 2000). Furthermore, the grain offered for sale by these cereal banks not only met industry standards, but was a recognizably superior product preferred by buyers. This is because smallholders who rely upon hand shelling and sorting are better able to differentiate grain quality during processing than when it is machine-harvested and shelled.

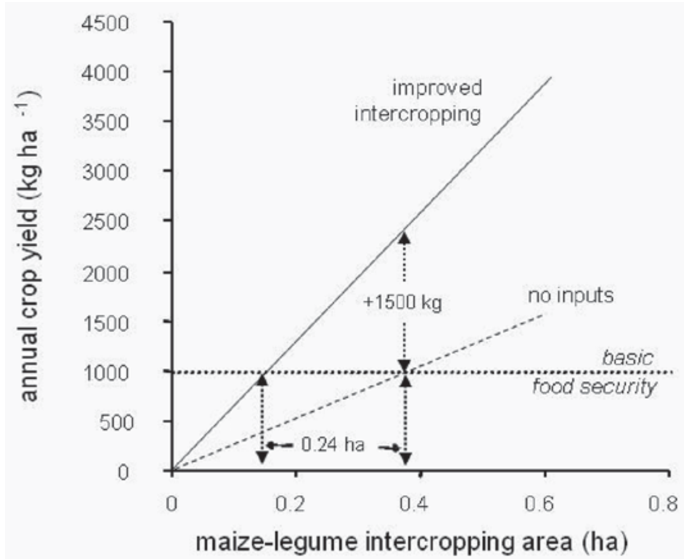



Figure 20.3. Household and economic advantages of adopting staggered maize-legume intercropping in west Kenya.

Given the nascent nature of farmer institutions, there is need to have intermediary institutions that can assist them in registration, negotiations, contract enforcement, quality improvement and local transportation. Such services cannot be provided through non-profit development agencies indefinitely, but rather these services should become privatized as income and employment generating activities. Ultimately, it is important that cereal bank coordination be recognized as a legitimate business opportunity by commercial lending institutions. Reliance on one profitable market, particularly millers in distant urban areas, is risky for farmers. To reduce these risks, cereal banks must also expand into other markets, particularly smaller-scale processors and local institutions such as schools and hospitals. Sound storage practices allow the local cereal banks to wait out the low prices following peak harvest in order to obtain a larger profit from their grain. Revolving credit and partial payment for deposited grain are important features within cereal banking because it provides access to capital at the farm level, allowing immediate payment to poorer farmers, thus providing additional incentive to participate. Conversely, members must be allowed to withdraw deposited grain whenever it is needed within their household. Looking ahead, this sort of collective marketing can also accelerate the uptake of improved production technologies among its members and offer modest, low-interest loans that allow them to purchase these inputs.

**Marketing small fertilizer packages and creating awareness on input use**

Repackaging farm inputs into smaller quantities is an important marketing mechanism worthy of a more detailed description. Within the strategy, farm inputs become more accessible and affordable to farmers, encouraging them to test new products without committing too much of their limited income toward farm experimentation. It is based on the principle that even the poorest households can afford simple necessities such as soap or salt, mainly because they are packaged and sold in small sizes by local shops. In late 1990s, the Sustainable Community Development Program (SCODP) in west Kenya adopted the strategy that fertilizers are one such commodity and combined the sales of small packages with widespread awareness creation and skill development in the use of mineral fertilizers and improved seed varieties. By repackaging farm inputs into smaller sizes (e.g. 100 g to 1 kg), they discovered the price at which even the poorest farmers were willing to invest in needed farm technologies. While SCODP purchased commercially available fertilizers in the standard 50 kg bags and repackaged and sold them for no profit (Seward and Okello 1999), other stockists were inspired to do the same but for commercial gain (Blackie and Albright 2005).

Following the success of SCODP and its early stockist innovators, many other retailers joined in repackaging. A survey of 139 retailers in 74 markets in Kenya showed that 79% were repackaging fertilizer in smaller quantities (Mwaura and Woomer 1999). By 2004, SCODP had sold 480 tons of fertilizer and 75 tons of improved maize seed to 45,000 households. Under SCODP intervention, fertilizer demand by all categories of small-scale farmers rose sharply as they became more familiar with and confident in the returns from fertilizer use (Kelly *et al.* 2003). With time, many farmers became interested in larger packages of 2, 5, or 10 kg with sales of 5 and 10 kg bags representing a quarter of all sales in many SCODP outlets. Farmers purchasing farm inputs from the SCODP network produced an estimated 5700 tons of additional maize by the end of 2004.

Evaluation of SCODP impact shows that women purchased between 40 to 70% of the mini-packs at different locations (Blackie and Albright 2005). The SCODP example illustrates how an intervention may lead to increased fertilizer use in SSA, even without subsidy or establishing expensive credit operations. It also shows that fertilizer use and food security is stimulated even amongst very poor farmers and that effective demand for inputs applied to food crops can be developed when the knowledge, skill, availability, and affordability constraints are addressed (Kelly *et al.* 2003). Farm Inputs Promotion Service (FIPS) is currently involved in the marketing of mini-packs of *Mavuno* blended NPKS fertilizer and in awareness creation on input use in SSA (see Chapter 12). Its honest broker focus in delivering inputs to farmers is a service desperately needed by poor, disadvantaged farmers. In this way, FIPS has provided a valuable and trusted market-friendly model for refining and adapting ISFM technology to local circumstances (Blackie and Albright 2005).

A similar experience with the mini-pack fertilizer marketing is the fertilizer micro-dosing with relatively low quantities of fertilizer (<20 kg $ha^{-1}$) through point placement in millet or sorghum-based systems (see Chapter 7) or through agronomically appropriate fertilizer management in maize-based systems (see Chapter 6). In West African Sahel, micro-dosing is used to allocate fertilizer providing healthy economic usage. The Food and Agriculture Organization has linked the *warrantage* inventory credit system to micro-dosing as a means of scaling-up ISFM packages (Bationo 2008).

The SCODP, FIPS and micro-dosing examples are certainly a great success in many ways. However, SCODP sold an average of only 10 kg per household. More should have been expected, but probably not without farm credit or subsidy. Too many demands compete for cash available to rural household, reducing their capacity for reinvestment. The elegance of ISFM is attributable to its combination of modest but respectable increases in fertilizer use with better management of organic resources resulting in the critical mass of nutrients necessary to productivity breakthroughs by small-scale farmers.

**Market linkage programs and increase in the use of ISFM**

Yield, output prices, and input costs are key variables that affect net returns and the incentive to use inputs (Crawford *et al.* 2003). The extent to which input use increases per unit land area depends on the payoff to extra inputs, a function of input:output price ratio and the marginal product of each input (Smith *et al.* 1994) and shows how unlinked input and output markets could depress the incentives for the adoption of ISFM. A review of African smallholder experiences with ISFM practices shows that the patterns of use vary considerably across heterogeneous agro-ecological conditions, communities and households, but are stimulated by profitable agricultural opportunities (Place *et al.* 2003). Contract farming often functions best when focused on cash crops with multiple commercial products and profitable business turnover (Collion and Rondot 2001).

Studies in sub-Saharan Africa have shown how ISFM significantly increases yields and quality of products. In Malawi, farmers who applied fertilizer had 105% more yield and 21-42% more profits than non-adaptors (Snapp *et al.* 2003). Legume intensification was also found to increase subsequent cereal yields by approximately 40%, with a net benefit increase of US \$50 $ha^{-1}$. Sanchez *et al.* (1997) give evidence of profitability of soil replenishment, increasing net farm incomes by 80 to 160%. Diverse soil fertility technologies, particularly those combining mineral fertilizers, organic inputs and intercropped legumes, have also provided positive economic returns in Kenya (Woomer 2007), especially in combination with striga control measures (Woomer 2008). In all cases, higher rates of return were recorded where ISFM was practiced. Part of the reason why the above cases were successful might be their limited scale of operations, not yet affecting output supplies as did with the Sasakawa Global 2000 experience in Ethiopia where unmarketable surpluses resulted from too widespread crop production campaigns.

Examples of market linkage programs that led to increase in fertilizer use in SSA include the micro-dose fertilizer applications and the *warrantage* systems in West Africa, and dual-purpose soybean and cowpea-maize rotations in northern Nigeria (Eaglesham *et al.* 1982) and Zimbabwe. Dairy markets in Kenya provide opportunities for farmers to use manure and raise money to invest in fertilizer. Others are the case of cotton in semi-arid West Africa (Defoer *et al.* 1995) and fertilizer repackaging SCODP and FIPS-Africa in Kenya. In a market garden program in Togo, small-scale farmers apply several hundred kilograms of fertilizers and over 10 t $ha^{-1}$ of manure to improve soil fertility for increased and sustainable production of vegetables (Debra 2003). Vegetable farmers in Cameroon directly phone D-O-U-A-L-A to ascertain ongoing prices to avoid exploitation by middlemen. This shows the potential role of ICT in input-output linkage for widespread adoption and impact of ISFM. The relationship between the activities of some of these programs and the use of ISFM has not been evaluated. However, there is ample evidence that in programs such as the *warrantage* system, input repackaging and the starter packs approaches have led to increases in the adoption of ISFM. Initial SCODP sales showed that the very small packs (1 kg and less) attracted most buyers. As confidence in the technology grew, farmers became more willingness to buy larger packs. In West Africa the combination of micro-dosing with complementary institutional and market linkage led to a significant breakthrough (A. Bationo, personal communication). In three years, about 5,000 farm households in 20 pilot sites started micro-dosing, producing 100% more food with 50% increase in farm income. Some NGOs (e.g., FIPS) are actively disseminating fertilizer sales in very small packets (100g) in East Africa. These programs provide evidence that demand for inputs can be developed among poor farmers if the availability, accessibility and affordability constraints are removed.

Most of the market linkage programs that lead to increased fertilizer use are also the ones where the returns to fertilizer use are high enough to warrant expansion in farmers' demand. Commercialization of smallholder agriculture, featuring high-value cash crops, can provide a strong stimulus to smallholder agriculture and have major indirect benefits for food crop productivity. This is not without problems. In southern Mali, although income from cotton made fertilizer investments possible, extreme soil degradation on other parts of the farm was reported because little fertilizer or manure was applied to adjacent food crops, lowering the soil organic matter below levels that protect soils from irreversible degradation (Van der Pol 1992).

Farmers need to be confident that investment in inputs will prove profitable, even when input use is small. One of the most important ways of maintaining interest in farming is to ensure that crop value remains considerably higher than the cost of production. For rain-fed food grain production, it is generally accepted that the value cost ratios (VCRs) must exceed 2 to motivate farmers to use mineral fertilizers given the risks involved. However, reported VCRs of fertilizer use on rain-fed food grain in West Africa rarely exceed 2, suggesting that returns to fertilizer use on food grain under rain-fed conditions without accompanying ISFM are too low to expand farmers' demand. Lack of well functioning input-output markets can reduce VCR, suppress agricultural productivity and exacerbate rural poverty in SSA.

Improved linkage between farm input and commodity markets will lead to more equity, especially if it is accompanied by improved market information systems. In Kenya, interlinked input-output marketing for cash crops has been shown to have the potential to promote food crop intensification (Jayne *et al.* 2004), demonstrating how institutional arrangement provides spillover benefits for overall farmer productivity. A review of studies across SSA indicates that fertilizer use could be as profitable in Africa as it is in Asia and Latin America (Yanggen *et al.* 1998).

**Market-led extension approaches**

For simple technologies such as fertilizer and seeds, market-led extension approaches are effective and have the advantage of linking input provision to output and financial markets, providing farmers with incentives to further invest in ISFM. In their article on expanding access to agricultural inputs in Africa, Kelly *et al.* (2003) argue for strengthening agro-dealers and rural stockists' networks. Given the large number of smallhold farmers using low rates of fertilizers, improvement in access has focused mainly on packaging fertilizers and seeds into smaller packets to increase their affordability, and networking of rural agro-dealers to provide better advice to farmers. Many more experiences across SSA give evidence of cases where market-led extension expands fertilizer use, however, a key problem with private extension is recovering their investments in services provided. The private sector is also generally considered weak for this role. It lacks organizational capacity, capital, human resources and the incentives to undertake large, risky and somewhat unattractive investments in rural areas (Doward *et al.* 2005). A number of problems need to be overcome prior to cost-effective commercial extension services to farmers. These problems include:

- Dysfunctional service delivery that occurs when farmers do not receive complementary extension services needed to practice ISFM. In many cases, inputs are not available on time.
- Rural markets tend to be thin, leading to high transaction costs of providing extension services to small-scale farmers and reducing the incentives for commercial service delivery to them.
- Market perversion that permits some private sector actors to exploit farmers through misinformation, product adulteration and dishonest measurements.
- Monopolistic opportunism that arises where limited commercial activity makes it possible for agro-dealers to exploit farmers through high cost of services.
- Strategic default or deliberate failure of farmers to adhere to terms of farm business contracts.
- Failure that arise when farmers demand for purchased inputs depends on unreliable access to finances, market access and complementary extension services.
- Limited farmers' voice making it difficult to hold the private and public sector service providers accountable for ineffective services.

Some market linkage programs are criticized because they lead to mining of the soil. Most of such programs lack ISFM, especially the need to optimally maintain soil fertility through a combination of organic and inorganic fertilizers (Defoer *et al.* 1995). This explains why some scholars caution against market-oriented farming saying that it requires financial commitments that many farmers do not have and may increase resource degradation (Van der Pol 1992; Snapp *et al.* 2003). Studies and observations in Uganda found that nutrient balances in banana and plantain production are negative, as up to 82% of nutrients in the bunches are exported to urban markets. Where produce markets are linked to well functioning input markets, like cotton farming in parts of West Africa, tobacco in southern Africa and cooperatives in the highlands of Kenya, it has been observed that farmers are able to reinvest their income into production and adoption of ISFM, leading to intensification and further increase in income.

**Small-scale pro-poor initiatives**

The choice of soil fertility management options is dependent upon the capacity of the farmer to afford related investment. In SSA, pro-poor initiatives have been conducted on a limited scale among farmers incompletely linked to markets (Omamo and Farrington 2004). Due to their limited potential for investment, some organic-based systems appear more attractive to a poor households that cannot access or afford inorganic fertilizers (Reardon *et al.* 1997; Place *et al.* 2003). The increasing value of groundnut and cowpea residues as marketable commodities in West Africa is generating income for poor farmers. At current adoption rates, the use of the legume residues has the potential to reach several million farmers with internal rate of returns of 50-103% (Kristjanson *et al.* 2002). Livestock manure is also marketed in northern Nigeria and Madagascar. These initiatives have the potential to create output markets in tandem with the promotion of input packages. If coupled with improvements in on-farm storage, such initiation can permit farmers to take advantage of inter-seasonal price variability (Howard *et al.* 2003).

**Innovative production and marketing ventures.** Production and marketing ventures are managed by empowered farmers' associations and supported by well equipped rural service providers. This approach permits producer associations to offer better access to farm inputs to their members during the cropping season and also guarantees access to produce markets at the end. Producer associations also broker information, test improved technologies, and help influence policy, creating incentives for greater adoption of ISFM.

Widespread integration of the activities farmers' organizations in innovative production and marketing ventures is an important means to avoid compartmentalization. Farmer organizations help members to overcome unfavorable economies of scale associated with individual operations attempting to acquire inputs and market their surplus produce (see Figure 18.1). They also have a major role to play in both accessing services (negotiation, coordination, delivery, etc.) and advocacy required to guarantee that the poor can benefit from ISFM investments. However, according to Poulton *et al.* (2005), despite the recent emergence of some promising farmer organizations, their track record is mixed. There is therefore, the need to investigate the conditions under which farmer organizations most effectively operate.

For competitiveness in the market, producers must continually look for ways to increase the efficiency and profitability of their production. Production ventures pay due attention to crops, livestock, and other enterprises where investment will benefit different categories of small-scale farmers and provide them with the needed resources. Investments must be on enterprises that expand market opportunities and involve identification of critical areas in the value chain where interventions can have wider impact and stimulate positive shifts (Sanginga *et al.* 2007). These investment options must address the needs of male and female farmers in marginal areas, and stimulate sustainable investments by all stakeholders to create impact at scale.

**Strengthening market information systems.** The aim of market information systems (MIS) is to diversify the sources of farm input supply and expand access to commodity buyers in a manner that directly benefits small-scale producers. Presently, market information is commonly conveyed through agro-dealers and commodity assemblers who are often selective in their messages provided. Lack of information, irregular access to it or one party having more information than another negatively affect market performance and development. Many a time, agro-input dealers are the sole sources of market information on farm inputs. Alternative channels and the use of modern information technologies (IT) are urgently needed. Effective MIS must be developed and made available to all stakeholders. The potential of MIS to increase market efficiency and strengthen the bargaining position and competitiveness of small-scale producers against traders and of smaller traders versus larger ones makes it an important mechanism. A number of innovative approaches for effective MIS provision are being piloted in

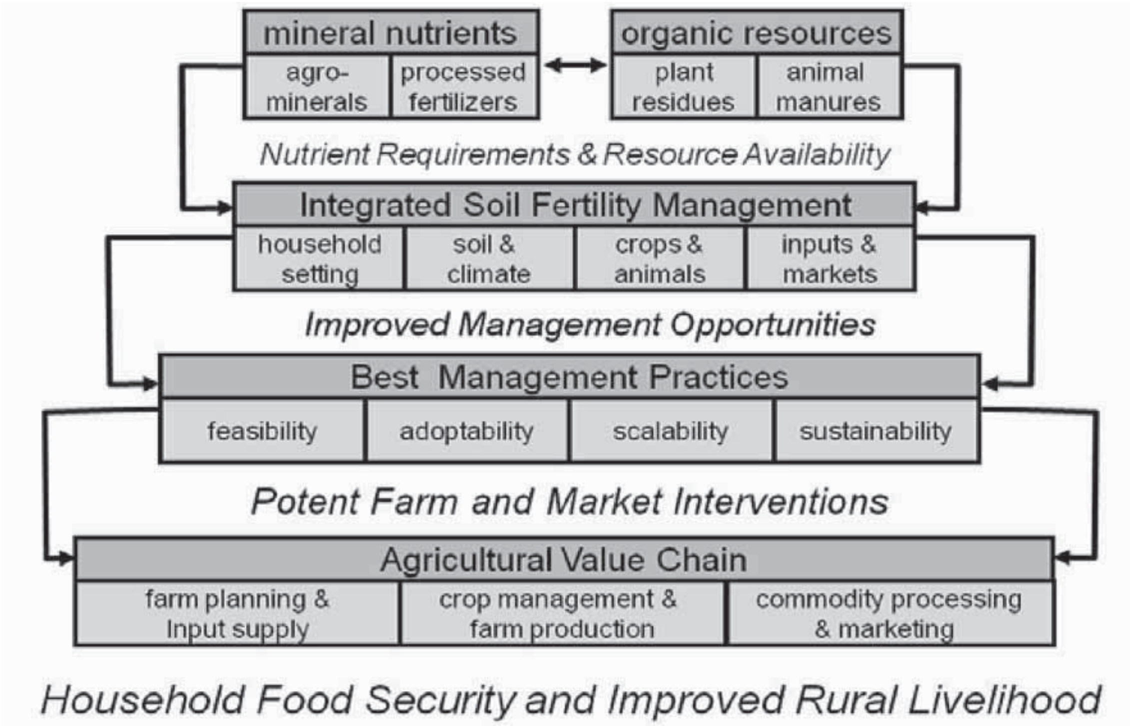



Figure 20.4. The hierarchical relations between resource requirements, management opportunities, market intervention and improved rural livelihood.

SSA, taking advantage of advances in IT, radios, cell phones, internet, and satellites to facilitate the spread of information.

**Alternative credit and finance markets.** Rural households require savings, credit, insurance, and money transmission to derive full benefit from improved marketing services. Successful financial service providers for poor rural areas in Africa include savings and credit co-operatives village banks, rotating savings and credit associations, and micro-finance institutions. Insurance provides incentives for the poor to assume greater risk. A challenge in developing incentives that accelerate widespread adoption of ISFM is that a great proportion of the target farmers are extremely poor. Seasonal credit and smart subsidies specific for ISFM are critical to accelerate widespread technology adoption and retention. Seasonal credit enables farmers to access and apply inputs that would otherwise be beyond their reach. Key components to this approach include providing loans to intermediary traders with inbuilt strategies to avoid default, establishing smart subsidies with clear exit strategies to relieve seasonal credit and cash constraints, arranging duty-free importation of fertilizers and agro-minerals and devising tax incentives to encourage needed farm inputs.

**Strengthening the agricultural value chain**

ISFM permits farmers to make the best use of gathered and purchased nutrients based upon their site-specific conditions and farming objectives (Chapter 1). These practices may be grouped into sets of best management practices (Chapter 12) and promoted within ISFM extension programs (Chapter 14) in order to take hold within rural communities. But the full benefits of ISFM, particularly household food security and improved rural livelihoods, can only become realized through their integration into agricultural value chains in terms of farm planning, input supply and commodity marketing (Figure 20.4).

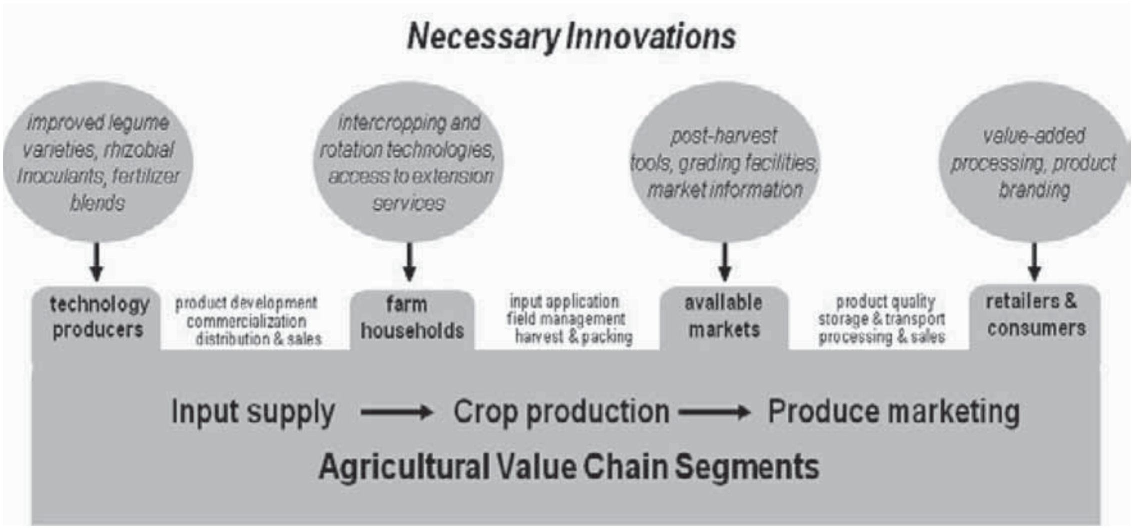



Figure 20.5. Promoting ISFM, grain legumes and their inoculants requires innovation along the entire agricultural value chain.

Expanding ISFM among African smallholders requires participation and innovation along the entire agricultural value chain. Needed product innovations include the development and release of improved crop varieties to seed producers, the identification of needed accompanying technologies such as seed coating and legume inoculants, blended special fertilizers and low cost agro-minerals (Figure 20.5). New products must also be accompanied with knowledge on handling and application. Extension messages on ISFM are required, and farm organizations will likely serve as an important means to deliver these new products and knowledge. Those organizations seeking to expand commodity processing and marketing services to their members must also provide tools and training to them as well. Opening new markets for produce and products requires that quality standards be met and transportation and storage difficulties be overcome. Indeed, the best way to expand ISFM practice and farm input use is to access fair markets with preferred products of reliable quality.

# Chapter 21. Advancing ISFM in Africa

The promotion of Integrated Soil Fertility Management must be viewed within the larger context as contributing to rural development agendas. These actions necessarily occur at local, national and regional levels and investments in ISFM must be consistent with needs of rural communities, the national priorities established for balanced agricultural and economic development, and regional initiatives designed to achieve greater self-sufficiency through closer ties and fair interdependency between African countries. This lofty placement of ISFM is not unfounded given that soil fertility decline is the leading cause of declining per capita food production in sub-Saharan Africa (Sanchez *et al.* 1997) and that industrial development is near impossible without preceding agricultural intensification (Eicher 1999). African leaders recently reinforced this underlying importance of soil fertility through their resolution to increase the region's fertilizer use from the current 8 to 50 kg nutrients $ha^{-1}$ by 2015 (Africa Fertilizer Summit 2006). The impact of achieving this target will, however, vary depending upon how efficiently increases in fertilizer use result in production and economic gains, and herein rests the importance of ISFM and the challenge to its proponents and practitioners.

ISFM does more than assist small-scale farmers to produce larger crop yields, but also improves household diets, recovers and manages soil health, reverses nutrient mining of soils, sequesters soil and biomass carbon to counter climate change, and offers a host of other economic, social and environmental services. These benefits are readily characterized by the variety of ISFM successes described throughout this book and summarized in Table 21.1. Despite geographic and logistic diversity, these successes share common features and the driving forces for achieving impacts at scale include technology sparks. These signals result from raised competence in land management leading to multiple benefits to practitioners, flexibility in dissemination approaches and parallel innovations in policy support and market development (Roose and Barthès 2001). Within this context, technology sparks result from simple to understand and acquire products and field practices that provide additional and obvious benefits to crop and farming system productivity. Market linkages support ISFM because it performs best where farmers have access to farm inputs, credit facilities, post-harvest storage and fair produce markets. While some of the existing policies support and enable ISFM, others are inimical to widespread ISFM adoption and must simply be removed.

## Recognizing technology sparks

The major successes of some technologies and practices mentioned in the preceding chapters are classified on the basis of ISFM characteristics, adoption potential and expected benefits (Table 21.1). The following set of strategic interventions focus on ISFM practices that improve the agronomic efficiency of fertilizer and applied organic inputs that are relevant to specific cropping systems and agro-ecological zones.

**Promote grain legumes in cereal- and cassava-based cropping systems.** Strategies must be designed that optimize the role of legumes within a wide range of smallholder cropping systems and the availability of these legume seeds improved. We must devise recommendations to better integrate legumes into systems and to target phosphorus sources and improved rhizobial inoculant delivery system that result in additional BNF by legumes, increase the availability of improved legume germplasm through local and formal seed systems and better organize legume production and marketing chains to quickly respond to commodity surpluses and shortages.

**Optimize and promote fertilizer micro-dosing and nitrogen top-dressing.** Optimal micro-dosing and top-dressing strategies must be refined and campaigns launched that promote their use. Applying fertilizers in micro-dose amounts permits more precise and better timed fertilizer

Table 21.1. Lessons learned from the ISFM success stories.

| Case studies | Role of fertilizers | Adoption prerequisites | Known and expected benefits |
|---|---|---|---|
| Fertilizer micro-dosing | Although quantities are small, the entry point is appropriate management of fertilizer | • Local availability of technology<br>• Extension and training<br>• Setting up *warrantage* system<br>• Credit systems (fertilizer, seed)<br>• Product storage infrastructure | • High return to fertilizer<br>• Yield gains 43-120% compared to non-adopters; income increase 52-134 %<br>• Increased food security<br>• Less need for food aid |
| ISFM linked to soil and water conservation | Fertilizers only applied when other growing conditions are favorable | • Village-level soil and water conservation structure in place<br>• Extension and training with NGOs<br>• Corralling agreements in place | • Combination of high WUE and AE allows profitable intensification<br>• Re-vegetation of rangelands due to intensification under ISFM<br>• ISFM options can be turned into best fit technologies |
| Dual purpose legume-maize rotations | Targeted P fertilizers help soybean fix high amounts N, on which maize partly scavenges; very high AE under proper management | • Availability of improved maize and soybean germplasm<br>• Access to input/output markets and credit facilities<br>• Organize production chain to respond to increased soybean demands | • Maize yields up by 1.2-2.3 fold compared to monoculture<br>• Net returns up by 50-70% compared to non-adopters<br>• Partial substitution of mineral fertilizer; N-fixation in Nigeria is worth at \$44M $yr^{-1}$ |
| Maize-legume inter-cropping systems | Targeted P fertilizers help legumes fix high amounts of N, on which maize partly scavenges; high AE likely under proper management | • Adjustments in row spacing and orientations<br>• Commercial legume and maize seed production<br>• Extension and training<br>• Additional benefits include suppression of *Striga*<br>• Rhizobial inoculants available | • Increased maize yield by 24%<br>• Partial substitution of mineral fertilizer<br>• Increased groundnut by 472 kg $ha^{-1}$ compared to non-adopters<br>• Potential benefits of \$88M when scaled up to 1M farmers |
| ISFM in conservation agriculture | Well-watered areas with undisturbed soils allow good returns to fertilizers applied as top-dressing | • Potential conservation tillage technology available that can be adapted to local conditions<br>• Extension and training<br>• Presence of inputs/output markets | • Doubling of maize yields realized<br>• Existing nutrients, organic C maintained<br>• High potential for scaling-up<br>• High potential in empty lands |
| ISFM for cassava-based systems | High population density and new markets for cassava justify fertilizer use | • Demand for cassava increasing<br>• Market integration needed<br>• Participatory R&D should yield attractive ISFM applications | • Substantial yield and production increases<br>• Increased market access for cassava growers<br>• Sustainable production under ISFM includes legume intercropping |
| ISFM for rice-based systems | NERICA highly responsive to fertilizers adjusted to indigenous nutrient supply | • Demand for rice increases<br>• Efficient access to consumer markets, extension and training | • Substantial yield and production increases<br>• Increased self-sufficiency in rice for SSA<br>• Increased urban food security |
| Large-scale use of phosphate rock | Rock phosphate can substitute for more costly imported soluble P fertilizers | • PR deposits within economic distance of the utilization areas<br>• Processing needed for many deposits | • Substantial foreign exchange savings through substation for imported fertilizer<br>• Substantial increases in yields through long-term soil P capital build-up |

placement, particularly in semi-arid areas where moisture availability constrains production. Top-dressing cereals with N-bearing fertilizers is a near universal requirement for highly profitable cereal and green vegetable production that is too seldom practiced by smallholders. In many cases, the fertilizers well suited for top-dressing are available but not used for that purpose. Timing micro-dosing and top-dressing to the rains is a skill required by farmers because it improves fertilizer use efficiency and reduces the consequences of drought.

**Improve P capital and use locally available phosphate rock deposits.** Greater effort must be made to assess the economic benefits from the addition of phosphate rock and means found to better process and distribute these fertilizer products for use by smallhold farmers. These deposits occur throughout Africa and may be used to supplement and substitute for imported mineral fertilizers. Sedimentary and igneous deposits vary greatly in terms of their nutrient concentrations and solubility, but many are able to be used in raw or semi-processed form, particularly when combined with applied organic resources. In other cases, we must improve our capacities to increase the solubility of less-reactive rocks through co-granulation or partial acidulation. Plans must be developed for better distribution and marketing of phosphate rock in areas with widespread phosphorus deficiency.

**Better mobilize other agro-minerals.** Local deposits of other agro-minerals, particularly limestone, dolomite and gypsum effectively correct pH, calcium, magnesium and sulfur imbalances. These deposits occur throughout Africa, and are often being mined for industrial purposes not involving fertilizer production. Clearly, benefit will be obtained from assessing the agronomic potential of current industrial by-products containing plant nutrients and then informing land managers of their comparative advantages.

**Fine-tuning soil management advice to farmers' local conditions**

Land management recommendations in Africa have too often failed to take farmers' traditional practices and their limited capacity for investment into account because they were developed using top-down diagnostic approaches and formulated using inappropriate economic models. On the other hand, ISFM appreciates the intricacies within small-scale farming systems and recognizes opportunities for improved nutrient management in a localized and stepwise context.

**Target nutrient additions per unit input.** Many fertilizer recommendations made to farmers are regarded as excessive and rightfully so. Fertilizer recommendations are generally based upon sound field trials, but too often, they are formulated by optimizing returns per unit area rather than unit input (see Figure 2.3). Recommended fertilizer rates based upon the greatest returns per unit input are usually 30% to 50% of those based upon unit area. This implies, for example, that if a farmer can only afford to fertilize 1/3 of the farm at the unit area recommended rate, then she is usually better off by applying only 1/3 of that rate to the entire farm. ISFM achieves greater agronomic efficiency from reduced fertilizer application and its combination with organic inputs.

**Reinforce traditional nutrient management practices with judicious addition of mineral fertilizers.** For example, composts may be fortified with rock phosphates, resulting in greater nutrient solubility and retention. Manure piles may be protected against nutrient loss resulting in lower amounts of mineral fertilizers required to supplement them. Farmers least able to afford mineral fertilizers should be provided special guidelines on how to use limited amounts of them most effectively.

**Accommodate additions of organic resources into recommendation domains.** Farmers with sufficient manure can substitute them for pre-plant fertilizers and invest more in top-dressed fertilizers later in the season. Fertilizer recommendations may also respond to the amount and placement of nitrogen-poor organic residues intended to boost soil organic matter and improve physical properties. Fertilizer recommendations must not only provide suggested types and rates but also offer guidelines on how to make adjustments in conjunction with the use of commonly available organic resources.

**Adjust recommendations to farmers' resource endowments.** Different resource endowment categories exist within a given farming community and the capacity of each category to invest in mineral fertilizers differs. Fertilizer recommendations have so far had little impact on smallholder production systems beyond those in the higher resource endowment category. Similarly, households have different degrees of labor availability, especially during periods of peak demand, that influence the feasibility of more tedious and knowledge intensive tasks. Farmers producing cereals for market should be offered one set of recommendations, and those seeking food security for least cost could be offered another, lower one where fewer fertilizers are used more efficiently. Thus fertilizer recommendations may be formulated along two parallel paths, one for strictly commercial production that optimizes returns per unit area at prevalent market conditions and another intended for resource poor farmers that makes the best use of limited available inputs.

**Recognize nutrient depletion as an ongoing and reversible process.** Soil nutrients represent resource capital that can be assigned value and supplemented through investment and labor. In some cases, soil nutrient depletion has exceeded critical thresholds that require ameliorative treatment quite different from routine crop management. Furthermore, soil health can be described using readily diagnostic parameters that identify severely degraded lands and influence farmer decision making. A separate suite of recommendations that allows farmers to rehabilitate their least productive fields in a resource and time efficient manner is required.

**Adjust management to spatial heterogeneity.** Spatial heterogeneity within and across farms results from topography, nutrient depletion and specialized land use, and these differences necessarily influence soil fertility management. In many cases, heterogeneity is intensified from past management when more resources are devoted to nearer or more productive fields. It is near impossible to capture individual farm level heterogeneity within extension recommendations, but different advice can be forwarded for major topographic units, such as valley bottoms, hillsides and plateaus and the major land management units contained within them in a way that leads to complementarity within farming enterprises.

**Involve farmers in formulating recommendations.** Participatory research methods guarantee farmers' role in the formulation of land management technologies, farmers' adaptive response to recommendations and the resulting impacts. This approach is markedly different from top-down, prescriptive approaches to fertilizer use. Localized fertilizer recommendations are best developed, adjusted and validated through close collaboration between researchers, extension agents, farmer associations and their members. Extension efforts should seek to assist farmers to undertake adaptive adjustments to those local recommendations by providing necessary information and field diagnostic tools.

**Carefully evaluate, validate and apply decision support tools.** Greater use must be made of available decision support tools, particularly plant and soil simulation models and geographic information systems (GIS). Models may be used to screen candidate recommendations and test their agro-ecological ranges. GIS allows for finer definition of recommendation domains.

Models and GIS may be interfaced to generate spatially-explicit model outputs describing responses to different land management strategies. Familiarly with plant and soil simulation models inspires system's thinking that may then be applied to specific production constraints. Improved fertilizer targeting may be achieved through the use of models and GIS, but time and resources spent initializing these tools must be balanced with and closely linked to localized, on-farm testing of ISFM practices.

**Building stakeholders' capacities in ISFM**

Training at several levels, from policymakers to farmers and particularly re-training of extension agents and national scientists is an essential component of widely-adopted ISFM. Furthermore, investments within individual countries must be coordinated and provided with up-to-date information on ISFM principles and practices. Lessons learned through failure or over many years of trial and error in one country need not be repeated in the same manner elsewhere. Managing individual investments in ISFM on a regional scale and as a network suggest the need for a Center of Excellence in ISFM.

**Balance public sector extension, community-based approaches and market-led promotion of ISFM.** There is ample evidence that reliance on more traditional extension approaches and farmer-to-farmer diffusion is successful in dissemination and uptake of ISFM technologies. This is particularly true when the technologies are less knowledge intensive, and do not require extensive adjustment of farming practices. While past extension efforts focused upon crop response to mineral fertilizer, the widening angle of extension and dissemination approaches based on better understanding of land management technologies views ISFM as more complex and challenging than just mobilizing seed and fertilizer packages.

Repeated failures of conventional extension approaches to dissemination led to the development of more participatory methods. Community-based organizations offer viable alternatives to government bodies by virtue of their intensive and client-focused working styles. Farmer participatory research is vital for re-orienting technology development, accelerating adoption and creating wider impacts of agricultural technologies in small-scale farming. Participatory extension methodologies have been widely employed as means to improve dissemination and adoption of ISFM technologies by building local capacity to conduct adaptive research, and for farmer-to-farmer dissemination. However, CBOs must not be backstopped by NGOs that express ideological biases against manufactured fertilizers and pesticides.

For simple, product-based technologies such as fertilizer and seeds, market-led extension approaches are very effective. These have the advantage of linking input provision to output and financial markets in a way that provide farmers with incentives to further invest in ISFM. Given the large number of small-scale farmers who use fertilizers at low rates, improved accessibility of fertilizers and seeds should focus upon repackaging of inputs into smaller quantities to increase affordability, and the development of agro-dealers networks able to provide accurate product information to farmers.

**Strengthen the capacities of African countries to implement ISFM as a component of their rural development agendas.** The capacity to implement ISFM must be strengthened at the level of international networks, NARS and extensions services, vocational schools and universities, non-governmental and community-based organizations and within the private sector. The research agenda for saving Africa's soils implies a re-orientation from conventional soil science approaches, the development of new skills, and a re-tooling of soil science laboratories.

Working with existing NGOs and farmer associations and their umbrella networks is important to promote ISFM. These groups represent a ready-formed audience for technical messages, will collectively undertake independent technology evaluation and provide necessary feedback and peer support on ISFM technologies. Furthermore, these groups can participate in innovative pilot efforts at ISFM technology dissemination such as voucher systems, revolving funds, and planned production and marketing ventures. Market-led technology adoption implies that improved profitability and access to market will motivate farmers to invest in new technology. Ideally, when farmers purchase fertilizers they should also be provided with accurate information on how best to use them.

Key developments to advance capacities in ISFM include the establishment and expansion of international networks with a critical mass of expertise to provide a key foundation for upgrading both physical and human capacity of African soil science. National scientists must be encouraged and supported to design ISFM practices and develop strategies for their dissemination. Extension staff must be retained for effective delivery of ISFM at the farm level. Educators must understand ISFM in theory and present it within school and university curricula. Finally, agro-dealers require training in distributing products and information that advance ISFM.

**Establish a Center of Excellence for ISFM.** A Center of Excellence for ISFM will backstop all capacity building activities and drive the generation of new knowledge and approaches to disseminate ISFM practices in a cost-effective manner. ISFM is an interdisciplinary pursuit with tremendous potential but scattered expertise. Need exists to concentrate some of this expertise in a manner that accelerates technical breakthroughs and provides training materials describing ISFM in a practical context. These experts will not be desk scientists, rather, members of this center would serve as a mobile cadre of ISFM practitioners prepared to assist in the design and implementation of country-level projects and be held responsible for trouble-shooting ISFM interventions.

Such a center would provide several services. It would synthesize ISFM principles into flexible field practices presented in ways best understood by farmers and rural development specialists. It would also design, field-test, and commercialize diagnostic soil test kits and fertilizer test strip packages suitable for Africa's highly weathered soils for use by extension agents, rural development specialists, and farmer associations. Finally, need exists to better harness new advances in spatial decision support systems, including GIS, remote sensing and diagnostic surveillance approaches, to improve regional planning of ISFM and targeting of appropriate advice and inputs to farmers.

**Identifying and enacting policies supporting ISFM**

Policy interventions facilitate the availability of specific ISFM products including agro-minerals, fertilizer and improved crop germplasm, and the integration of ISFM into national and regional development initiatives.

**Integrate ISFM into poverty reduction strategies.** Strategies should be developed to effectively integrate ISFM into informed national and regional fertilizer promotion, agricultural development and poverty reduction efforts. This intervention option would establish mechanisms for capacity building, institutional learning, policy dialogue and advocacy at different levels to bring about reforms favoring all stakeholders, especially the rural poor. Achieving this goal requires a review of national agricultural development strategies to identify gaps relating to soil management, and then developing alternative policies addressing those gaps.

**Facilitate enabling policies for seeds and fertilizer.** Effective seed systems are critical for accelerated and widespread adoption of ISFM and strategies must be developed to overcome the limited interest of commercial seed sector in self-pollinating legumes. Along the same lines, there is the need to facilitate and promote seed associations and community-based seed production.

There is also the need to reformulate regulations on repackaging farm inputs that provide quantities affordable to farmers while assuring product quality. Instituting strong penalties for product adulteration are preferable to banning the repackaging of farm inputs.

**Improving agricultural market linkages**

**Better coordinate input-output markets related to ISFM**. The lack of coordination in input-output markets often means that programs focusing on either input supply or produce marketing alone often fail because of the absence of complementary investments in the other aspects of the supply chain. Coordination of the supply chain involves the development of an effective system to support investments and services by different players. Better linkages to credit and fair commodity markets increase productivity and returns to investments in ISFM because farmers better benefit from crop surpluses. Means must be found to support agro-dealers, micro-finance agencies, and farmer associations to provide services advancing ISFM and to promote higher value crops, prolonged shelf life and value added products.

**Provide seasonal credit, loans, and other incentives.** Several incentives relating to ISFM are critical to accelerate widespread adoption and retention of new land management technologies. Key components in these areas include providing loans to intermediary traders with inbuilt strategies to avoid default, devising smart subsidies with clear exit strategies to relieve seasonal credit and cash constraints, allowing duty-free importation of fertilizers and agro-minerals, and offering tax incentives to encourage legume seed production and access to rhizobial inoculants.

## Conclusions

The Integrated Soil Fertility Management paradigm, as defined and elaborated throughout this book offers an alternative to the so-called Second Paradigm that identified fertilizer as the key entry point for improving productivity of cropping systems in developing nations (Sanchez 1994). The ISFM paradigm recognizes that applying organic resources in conjunction with fertilizers offers immediate and longer-term economic and environmental advantages and a positive interactive effect upon farm enterprise development. ISFM places importance upon an enabling environment that permits farmer investment in soil fertility management, and the critical importance of farm input suppliers and fair produce markets. In this way, ISFM is a holistic approach that not only requires land managers to invest in external farm inputs, better recycle available organic resources and foster beneficial soil biological processes (Uphoff *et al.* 2006), but also provides additional incentives and strengthened understanding for them to do so.

The key components to supporting ISFM development and adoption involve actions by international, national and local bodies. International networks are required to establish the critical mass of expertise needed for upgrading both physical and human capacities of soil science in Africa. National scientists must be encouraged to adopt ISFM philosophies, design innovative soil fertility management practices, and develop strategies for their dissemination. Extension staff must be retrained for effective delivery of ISFM technologies at the farm level. ISFM theory and practice must feature within vocational school and university curricula and community-based organizations must be mobilized to promote ISFM. Agro-dealers must be trained in accessing, managing, and distributing products advancing ISFM and their accompanying information. Formal and indigenous knowledge systems must become better integrated to allow farmer associations to recognize, adapt, and implement ISFM practices. It is hoped that this book not only raises awareness and understanding of Integrated Soil Fertility Management, but will prompt action by the research and development community to include its approaches into their agendas for African food security, poverty alleviation and rural transformation.

# Appendix

Appendix 1. Mineral nutrient contents of some common organic resources (based upon the TSBF Organic Resource Data Base)

| Material | Part analyzed | N | P | K | Ca | Mg | Lignin | Total Soluble PP |
|---|---|---|---|---|---|---|---|---|
| | | ------------------------- kg ton$^{-1}$ ---------------------- | | | | | | |
| **Agroforestry Species** | | | | | | | | |
| *Acacia sp* | leaf | 25.3 | 1.7 | 10.6 | 7.2 | 2.4 | 144.5 | 99.6 |
| *Adanisonia digitata* | leaf | 35.3 | 3.6 | 25.5 | . | . | . | . |
| *Albizia sp* | leaf | 34.5 | 1.8 | 4.1 | 7.3 | 3.0 | 106.0 | 33.4 |
| *Alnus acuminata* | leaf | 16.0 | 1.6 | 3.4 | . | . | 211.4 | 47.1 |
| *Azadirachta indica* | leaf | 18.4 | 1.6 | 22.2 | 15.7 | 2.0 | 220.4 | 55.7 |
| *Balanites aegyptiaca* | leaf | 30.7 | 1.4 | 32.7 | 31.4 | 6.2 | . | . |
| *Bambusa vulgaris* | leaf | 15.9 | 1.5 | 17.2 | 3.7 | 3.8 | 81.1 | 5.6 |
| *Calliandra calothyrsus* | leaf | 32.8 | 1.7 | 8.5 | 10.6 | 3.1 | 165.5 | 94.6 |
| *Calliandra calothyrsus* | leaf litter | 20.4 | 0.9 | 2.3 | 9.3 | . | 189.7 | 52.6 |
| *Calliandra calothyrsus* | prunings | 29.1 | 2.3 | 12.8 | 5.5 | . | 154.5 | 142.1 |
| *Cassia siamea* | leaf | 34.8 | 2.4 | 16.1 | 12.9 | 1.6 | . | . |
| *Chamaecytisus palmensis* | prunings | 32.5 | 1.2 | 5.9 | 10.5 | . | 69.0 | . |
| *Cocos nucifera* | leaf | 8.5 | 1.1 | . | . | . | 76.5 | 27.4 |
| *Coffea robusta* | leaf | 28.0 | 1.9 | 27.5 | 11.4 | 2.6 | 152.7 | 71.7 |
| *Croton macrostachyus* | leaf | 43.4 | 2.5 | 32.5 | 8.7 | 5.9 | 63.3 | 31.1 |
| *Croton megalocarpus* | leaf | 27.1 | 2.5 | 24.4 | 17.1 | 4.4 | 140.8 | 23.4 |
| *Dactyladenia barteri* | leaf | 17.3 | 0.9 | 6.0 | 9.2 | 2.0 | 213.8 | 41.7 |
| *Eucalyptus camaldulensis* | leaf | 10.7 | 0.7 | 2.4 | 17.1 | 2.3 | 58.0 | 75.4 |
| *Gliricidia sp* | leaf | 31.4 | 1.4 | 10.6 | 17.1 | 3.0 | 136.4 | 13.9 |
| *Grevillea robusta* | prunings | 15.1 | 0.8 | 10.8 | 1.0 | 1.8 | 240.8 | 45.7 |
| *Inga edulis* | prunings | 23.6 | 1.8 | 12.5 | 7.4 | 1.7 | 238.2 | 42.1 |
| *Leptospermum petersonii* | leaf | 18.9 | 3.0 | 14.0 | 11.1 | 3.0 | 343.3 | 97.9 |
| *Maesopsis eminii* | leaf | 27.2 | 1.6 | 11.0 | 13.8 | 6.1 | 113.9 | 28.0 |
| *Markhamia lutea* | leaf | 22.2 | 1.5 | 15.3 | 16.6 | 3.2 | 232.8 | 34.1 |
| *Morus alba* | prunings | 27.8 | 1.6 | 24.1 | 31.6 | 4.9 | . | . |
| *Psidium guajava* | leaf | 23.3 | 2.0 | 15.4 | 9.4 | 3.2 | 19 .2 | 138.6 |
| *Pterocarpus santalinoides* | leaf | 3 .1 | 1.1 | 12.3 | 13.9 | 3.8 | 241.0 | 26.3 |
| *Rhus natelensis* | leaf | 24.4 | 1.9 | 34.7 | 12.2 | 4.8 | 52.5 | 4.0 |
| *Samanea saman* | leaf | 39.9 | 1.4 | 8.2 | 23.6 | 2.8 | . | 67.0 |
| *Schinus molle* | leaf | 28.2 | 1.9 | 16.1 | 13.7 | 5.9 | 99.5 | 48.0 |
| *Senna sp* | prunings | 23.4 | 1.3 | 13.0 | 14.3 | 2.1 | 133.8 | 25.4 |
| *Sesbania sesban* | leaf | 34.7 | 2.1 | 14.0 | 18.4 | 3.6 | 50 .7 | 58.9 |
| *Sesbania sesban* | leaf litter | 28.8 | 1.4 | 9.5 | 12.2 | 2.3 | 142.8 | 32.1 |
| *Spathodea canipulata* | leaf | 19.8 | 1.9 | 16.6 | 22.1 | 3.5 | 245.0 | 44.5 |

| Material | Part analyzed | N | P | K | Ca | Mg | Lignin | Total Soluble PP |
|---|---|---|---|---|---|---|---|---|
| | | ----------------------- | | | kg $ton^{-1}$ | | ---------------------- | |
| Agro-industrial by-products | | | | | | | | |
| *Coffea robusta* | husk | 16.7 | 1.3 | 29.0 | . | 1.8 | 3 9.6 | 13.8 |
| *Oryza sativa* | husk | 6.3 | 1.4 | 3.8 | 0.8 | 0.4 | 166.6 | 0.1 |
| *Vitis vinifera* | leaf | 33.4 | 2.4 | 24.9 | 8.2 | 4.8 | 54.3 | 26.5 |
| Animal manures | | | | | | | | |
| Cattle manure | dry | 9.8 | 2.2 | 8.5 | 4.0 | 2.3 | 84.8 | 1.7 |
| Cattle manure | fresh | 15.0 | 5.4 | 6.4 | . | . | . | . |
| Goat manure | composite | 15.0 | 4.0 | 5.3 | . | . | . | . |
| Pig manure | composite | 2.0 | 11.9 | 4.9 | . | . | . | . |
| Poultry manure | composite | 28.8 | 15.8 | 22.5 | 32.0 | 6.9 | 119.3 | . |
| Rabbit manure | composite | 16.0 | 4.0 | 5.0 | . | . | . | . |
| Sheep manure | composite | 12.8 | 4.7 | 57.7 | 11.0 | 14.5 | 51.8 | . |
| Composts | | | | | | | | |
| Compost | Mixed waste | 18.2 | 10.0 | 15.1 | 30.6 | 5.7 | 76.4 | . |
| Tree litter compost | mixed | 14.7 | 1.1 | 3.8 | 2.2 | 3.2 | 188.5 | . |
| | | | | | | | | |
| Crop residues | | | | | | | | |
| *Arachis hypogaea* | leaf | 32.5 | 1.8 | 24.1 | 13.4 | 4.0 | 50.8 | 28.7 |
| *Cajanus cajan* | leaf litter | 19.9 | 1.0 | 1.8 | 14.7 | 2.4 | 23 .7 | 31.0 |
| *Cajanus cajan* | prunings | 23.9 | 1.5 | 12.4 | 5.7 | . | 15 .5 | 52.3 |
| *Cajanus cajan* | leaf | 34.1 | 1.9 | 15.3 | 15.6 | 2.5 | 11.9 | 28.0 |
| *Cicer arietinum* | leaf | 41.7 | 2.7 | 28.8 | . | 4.6 | . | . |
| *Glycine max* | prunings | 26.9 | 1.9 | 21.6 | . | . | 85.3 | 17.7 |
| *Helianthus annuus* | leaf | 24.1 | 18.0 | 29.3 | 23.5 | 7.3 | 154.7 | 36.6 |
| *Ipomoea pandurata* | leaf | 23.2 | 3.6 | 46.9 | 9.8 | 3.9 | 96.4 | 40.8 |
| *Lablab purpureus* | leaf | 39.0 | 2.0 | 15.3 | 17.5 | 4.0 | 68.4 | 21.2 |
| *Lablab purpureus* | prunings | 30.2 | 2.5 | 24.7 | 14.0 | 2.6 | 54.0 | . |
| *Lablab purpureus* | leaf litter | 29.4 | 2.3 | 8.8 | 20.2 | 4.1 | 157.7 | 7.8 |
| *Lablab purpureus* | stem | 13.3 | 1.9 | 12.4 | 10.3 | 4.0 | 149.5 | 3.3 |
| *Manihot esculenta* | leaf litter | 29.8 | 1.9 | 7.3 | 10.9 | 5.6 | 375.2 | . |
| *Musa sp* | leaf | 19.0 | 1.2 | 21.9 | 11.6 | 3.2 | 107.5 | 11.4 |
| *Musa sp* | stem | 6.0 | 1.2 | 39.7 | 3.9 | 3.0 | 54.9 | 0.1 |
| *Oryza sativa* | leaf litter | 8.5 | 0.6 | 13.6 | 3.8 | 1.6 | . | . |
| *Phaseolus vulgaris* | leaf | 37.2 | 2.6 | 27.5 | 15.6 | 3.6 | 62.0 | 23.9 |
| *Phaseolus vulgaris* | stover | 9.9 | 1.1 | 19.3 | 9.2 | 2.6 | 108.2 | 3.4 |
| *Pisum sativum* | stover | 13.7 | 0.8 | 11.1 | 14.1 | 2.6 | 82.0 | 16.0 |
| *Saccharum officinarum* | stover | 3.9 | 0.4 | 7.0 | 2.4 | 0.4 | 160.2 | 3.5 |
| *Sorghum bicolor* | leaf | 6.3 | 1.0 | 14.0 | 4.9 | 1.4 | 42.3 | 29.2 |
| *Vigna radiata* | leaf | 34.5 | 1.6 | 16.9 | . | 5.2 | 33.8 | 29.5 |
| *Vigna unguiculata* | prunings | 24.2 | 3.1 | 11.0 | 12.2 | 7.1 | 127.0 | 11.1 |
| *Voandzeia subterranea* | leaf | 35.9 | 2.0 | 20.0 | . | 3.8 | . | . |
| *Zea mays* | leaf | 13.8 | 1.3 | 11.5 | 2.2 | 1.9 | 129.0 | 7.7 |

| Zea mays | stover | 8.3 | 0.8 | 12.5 | 3.4 | 1.9 | 88.2 | 7.4 |
|---|---|---|---|---|---|---|---|---|
| Material | Part analyzed | N | P | K | Ca | Mg | Lignin | Total Soluble PP |
| | | ------------------------- kg ton$^{-1}$ ---------------------- | | | | | | |
| Green manures | | | | | | | | |
| *Canavalia brasiliensis* | leaf | 37.1 | 2.7 | 17.9 | 10.4 | 3.5 | 65.2 | 84.0 |
| *Crotalaria sp* | leaf | 41.6 | 1.9 | 13.5 | 15.6 | 3.7 | 66.9 | 15.9 |
| *Desmodium intortum* | leaf | 32.9 | 1.4 | 21.0 | 14.5 | . | 77.0 | 47.6 |
| *Desmodium intortum* | prunings | 21.5 | 1.5 | . | 5.2 | . | 164.9 | 113.3 |
| *Desmodium uncinatum* | leaf | 30.9 | 1.6 | 19.7 | 16.3 | . | 116.6 | 49.8 |
| *Desmodium uncinatum* | prunings | 34.5 | 2.8 | 18.1 | 7.8 | . | 85.2 | 31.2 |
| *Glycine wightii* | prunings | 26.7 | 2.3 | 13.2 | 14.4 | 3.9 | . | . |
| *Lantana camara* | prunings | 19.7 | 1.8 | 29.0 | 9.9 | . | 152.4 | 33.9 |
| *Lantana camara* | leaf | 29.7 | 2.7 | 22.9 | 12.7 | 4.5 | 144.8 | 63.1 |
| *Leucaena sp* | prunings | 30.5 | 1.8 | 15.7 | 10.1 | 3.8 | 164.7 | 71.6 |
| *Mucuna deeringiana* | prunings | 13.7 | 1.7 | 5.8 | . | 3.8 | 104.5 | 29.7 |
| *Mucuna pruriens* | leaf | 44.1 | 3.0 | 15.5 | 10.0 | 4.5 | 86.8 | 75.2 |
| *Mucuna pruriens* | prunings | 29.3 | 2.3 | 15.3 | 9.0 | 5.4 | 78.6 | 88.1 |
| *Pennisetum purpureus* | leaf | 22.5 | 1.3 | 21.0 | 12.6 | 1.4 | 47.1 | 1.8 |
| *Tephrosia vogelii* | leaf | 21.4 | 1.0 | 8.2 | 14.6 | 2.9 | 1 6.8 | 63.9 |
| *Tithonia diversifolia* | leaf | 38.4 | 3.8 | 45.5 | 19.5 | 4.1 | 116.6 | 34.6 |
| *Tithonia diversifolia* | stem | 20.0 | 2.0 | 47.8 | 7.8 | 3.0 | 115.8 | 11.6 |

# Abbreviations and acronyms

| | |
|---|---|
| AATF | African Agricultural Technology Foundation |
| AE | Agronomic Efficiency |
| AEZ | Agro-ecological Zones |
| AfNet | African Network for Soil Biology and Fertility |
| AfDB | African Development Bank |
| AFS | African Fertilizer Summit |
| AGMARK | Agricultural Market Development Trust |
| AGRA | Alliance for a Green Revolution in Africa |
| AMF | Arbuscular Mycorrhizal Fungi |
| BMGF | Bill and Melinda Gates Foundation |
| BNF | Biological Nitrogen Fixation |
| CABI | Commonwealth Agricultural Bureau International |
| CAADP | Comprehensive Africa Agriculture Development Programme |
| CBO | Community-Based Organization |
| CAN | Calcium Ammonium Nitrate |
| CGIAR | Consultative Group on International Agricultural Research |
| CIAT | International Centre for Tropical Agriculture |
| CIDA | Canadian International Development Agency |
| CIMMYT | International Maize and Wheat Improvement Centre |
| CIRAD | Centre de Coopération Internationale en Recherche Agronomique pour le Développement |
| CNFA | Citizen Network for Foreign Affairs |
| COSCA | Collaborative Study of Cassava in Africa |
| CTIC | Conservation Technology Information Center |
| DAP | Diammonium Phosphate |
| DSSAT | Decision Support Systems for Agrotechnology Transfer |
| EU | European Union |
| FAO | Food and Agriculture Organization of the United Nations |
| FAOSTAT | Food and Agriculture Organization of the United Nations Statistics Database |
| FIPS | Farm Inputs Promotion Service |
| FFS | Farmer Field School |
| FORMAT | Forum for Organic Resource Management and Agricultural Technologies |
| FOTL | Farmers' Own Trading Limited |
| GIS | Geographic Information System |
| GFAR | Global Forum for Agricultural Research |
| HIV/AIDS | Human Immunodeficiency Virus-Acquired Immuno-deficiency Syndrome |
| IAEA | International Atomic Energy Agency |
| ICRAF | International Center for Research in Agroforestry (World Agroforestry Centre) |
| ICRISAT | International Crops Research Institute for the Semi-Arid Tropics |
| IDRC | International Development Research Centre |
| IFAD | International Fund for Agricultural Development |
| IFDC | International Center for Soil Fertility and Agricultural Development |
| IFPRI | International Food Policy Research Institute |
| IGAD | Intergovernmental Authority on Development |
| IIASA | International Institute for Applied System Analysis |
| IITA | International Institute of Tropical Agriculture |
| ILRI | International Livestock Research Institute |
| IPM | Integrated Pest Management |
| IRRI | International Rice Research Institute |

| | |
|---|---|
| ISFM | Integrated Soil Fertility Management |
| ISRIC | International Soil Reference and Information Centre |
| ITC | International Institute for Geo-Information Science and Earth Observation |
| KARI | Kenya Agricultural Research Institute |
| MDG | Millennium Development Goals |
| MEA | Millennium Ecosystem Assessment |
| MIS | Market Information Systems |
| MMM | Maize Marketing Movement |
| MOA-NAL | Ministry of Agriculture National Agricultural Laboratories |
| NEPAD | New Partnership for African Development |
| NGO | Non-Governmental Organization |
| NUTMON | Nutrient Monitoring |
| OECD | Organization for Economic Cooperation and Development |
| PIC | Phosphate Institute of Canada |
| PPI | Potash and Potash Institute |
| RELMA | Regional Land Management Unit |
| RUSEP | Rural Sector Enhancement Program |
| SACRED | Sustainable Agriculture Center for Research, Extension and Development |
| SIDA | Swedish International Development Agency |
| SCOPD | Sustainable Community Development Program |
| SOC | Soil Organic Carbon |
| SOM | Soil Organic Matter |
| SOTER | Soil and Terrain Digital Database |
| SSA | Sub-Saharan Africa |
| SWAT | Soil and Water Analysis Tool |
| TSBF | Tropical Soil Biology and Fertility Institute |
| UNDP | United Nations Development Programme |
| UNEP | United Nation Environment Programme, |
| UNESCO | United Nations Education Scientific and Cultural Organization |
| UN | United Nations |
| UWONET | Uganda Women's Network |
| WARDA | Africa Rice Center (West Africa Rice Development Association) |
| WeRATE | Western Regional Alliance for Technology Evaluation |

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# About this book, editors and contributors

## About this book

The Bill and Melinda Gates Foundation is investing in soil health as an important component of the African Green Revolution, a thrust that is intended to bring food security and improve the living standards of millions of poor, small-scale farmers in sub-Sahara Africa. During 2007, the Foundation commissioned the Tropical Soil Biology and Fertility Institute of CIAT to develop a series of concept papers and technical reports on Integrated Soil Fertility Management for its internal use in designing an African Soil Health Initiative. In response to that challenge, a team of fifteen experts was drawn from Africa and elsewhere to prepare these reports that later served as the structure for the development of this book, an effort that was further assisted by a grant from the Foundation. This grant permitted 4000 copies of this book to be printed by the United Nations of Nairobi Printing Unit and distributed free-of-charge to development specialists, educators, extension specialists and agricultural scientists throughout Africa. Those requiring a copy of this book are invited to contact TSBF-CIAT in Nairobi.

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# Index

# Integrated Soil Fertility Management In Africa: Principles, Practices and Developmental Process

**Edited by**
**Dr. Nteranya Sanginga (TSBF-CIAT)**
**and Dr. Paul L .Woomer (FORMAT)**

This reference manual prepared by TSBF-CIAT and its international team of experts improves understanding and increases application of Integrated Soil Fertility Management (ISFM) in Africa. It combines current knowledge of soil fertility management by African smallholders with recent breakthroughs in the state-of-the art and is intended to strengthen ISFM practice among land managers, agriculturalists, and rural development specialists. This book is separated into four major sections addressing the underlying principles, field practices, developmental processes and social dimensions of advancing ISFM in Africa, guiding readers through better land management strategy in a stepwise, comprehensive manner.

(21 Chapters, 263 pp.)

**Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture (TSBF-CIAT)**