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Soil Fertility Management Research for the Maize Cropping Systems of Smallholders in Southern Africa: A Review

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Abstract: This paper examines the implications of declining soil fertility for the maize-based cropping systems in southern and eastern Africa. A review of the importance of maize in the region is followed by a description of the economic and agronomic circumstances of smallholders who produce maize. Next, the paper examines technologies currently available for enhancing soil fertility, including technologies for increasing inorganic/organic fertilizer use and fertilizer-use efficiency and the development of maize genotypes that perform well despite low soil fertility. Ways of facilitating farmers' adoption of better soil fertility management practices are described, based on examples drawn from recent research, particularly in southern Africa. A new model for soil fertility research and extension is proposed. The model features the use of organic as well as inorganic sources of nutrients and actively involves farmers and others in an integrated, long-term process for improving soil fertility in southern and eastern Africa.

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Executive Summary

The dominant smallholder cropping systems of southern Africa are based on maize. Increasing human population density and declining land availability have made shifting cultivation obsolete, and maize is now continuously cropped in many areas. The fallows which traditionally restored soil fertility and reduced the buildup of pests and diseases are disappearing from the agricultural landscape. The soil resource is being degraded, with a consequent reduction in crop yield.

Despite the notable adoption of high-yielding maize by smallholders in Africa (improved germplasm is grown on 33-50% of Africa's maize area), national per-hectare increases in maize productivity are disappointing. Losses of mineral nutrients from soil generally exceed nutrient inputs. Presently the challenge of improving productivity without compromising sustainability is so large that farmers will need to combine gains from improved germplasm with complementary improvements in their management of soil fertility. Improved germplasm alone will not be sufficient to meet the challenge. Both research and extension organizations must place far greater emphasis on the complex issues related to building up and maintaining soil fertility under the income and other constraints faced by smallholders.

Inorganic fertilizers are expensive and not very profitable for smallholders to use, especially because impractical blanket applications of fertilizer are recommended even in semiarid areas. The profitability of using fertilizer must be increased for farmers who can afford fertilizer. This urgent task can be accomplished by developing improved fertilizer management techniques that are appropriate for smallholders and by ensuring that recommendations are better targeted to smallholders' circumstances.

Fertilizer-use efficiency is often low because of the declining level of organic matter in tropical soils. For this reason, the proportion of locally produced organic materials must be increased to maintain soil organic matter and halt the downward spiral of soil fertility. Improving the efficiency of inorganic fertilizer use in various ways, including the addition of soil micronutrients and small amounts of high-quality organic matter, will consolidate and expand the base of fertilizer users.

In many households, the cash required to buy inorganic fertilizer far exceeds total annual cash income. The lack of cash dominates decision making at the household level and is central to the development of adoptable technologies. Many farm households are forced to sell their labor in return for food or cash, which, in turn, compromises their own agricultural efforts. For this expanding group of farmers, the best strategy for increased soil fertility is to give more emphasis to organic sources of nutrients, especially legumes, that capitalize on the freely available nitrogen in the atmosphere.

Legumes are not new to farming systems. Grain legumes, legume intercropping and rotations, green manures, improved fallows, agroforestry, cereal residues, and animal manures can all enhance soil fertility and sustain the resource base. However, in broad terms, the larger the soil fertility benefit from a legume technology is likely to be, the larger the initial investment required in labor and land, and the fewer short-term food benefits it has. The potential of such technologies is rarely realized on farmers' fields.

Although combinations of low rates of several inputs show promise, especially combinations of inorganic and organic fertilizer, such combinations still have a cash cost. Innovative mechanisms are needed to help farmers begin to access such inputs. One promising approach involves providing farmers with start-up grants of cash paid into savings schemes, from which farmers can obtain loans.

Basic, process-based research provides the foundation for extrapolating from site-specific trials to agronomic recommendations for specific agroecological zones and farmer groups. Past crop husbandry research is often neglected because the results are distilled into a few recommendations that ignore the important interactions in the system and fail to address the widespread diversity that exists among smallholders. Institutional memory not only needs to be maintained but must be expanded to a wider group, in part through computer databases and effective networks. The emphasis in both research and extension needs to move away from a rigid and prescriptive approach to a flexible problem-solving format leading to conditional recommendations. This will facilitate the evolution of a technology development process driven by smallholders' needs. Failure to develop such a process will result in a weakening natural resource base and a continuing decline in the standard of living of rural communities reliant on agriculture in southern Africa.

Soil Fertility Management Research for the Maize Cropping Systems of Smallholders in Southern Africa: A Review

John D.T. Kumwenda, Stephen R. Waddington, Sieglinde S. Snapp,
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Introduction

It is increasingly evident that declining soil fertility is the most widespread, dominant limitation on yields of maize (*Zea mays* L.) and on the sustainability of maize-based cropping systems in southern and eastern Africa. Technologies that smallholders can use to sustain soil fertility are still relatively scarce. If researchers and farmers do not make a more vigorous attempt to address the extensive decline in soil fertility, the productivity of maize-based farming systems will fail to increase, and improved maize germplasm will have only a transitory effect on productivity in smallholders' fields.

In this paper, we explore strategies for building up and maintaining soil fertility in southern and eastern Africa despite the income constraints — and, increasingly, land and labor constraints — facing smallholders. We draw heavily on examples from southern Africa, particularly Malawi and Zimbabwe, for three reasons. First, our experience there is considerable. Second, Malawi and Zimbabwe offer contrasting portraits of an agriculture in crisis, increasingly unable to meet national food needs (Malawi), and one of the most successful agricultural bases in sub-Saharan Africa (Zimbabwe). Third, the experience with soil fertility constraints in southern Africa is relevant to many other areas of sub-Saharan Africa.

We begin with an overview of maize in southern and eastern Africa: its importance for food security, the conditions under which small-scale farmers grow the crop, and the evidence that even as more farmers turn to improved maize for higher yields, these efforts are frustrated by a persistent decline in soil fertility that reduces productivity. Next, we look at technologies currently available for enhancing soil fertility and proceed to outline, based on examples drawn from practice, ways of facilitating farmers' adoption of better soil fertility management practices. We then propose a model for soil fertility research and extension that features the use of organic as well as inorganic alternatives and actively involves farmers and others in an integrated, long-term process for improving soil fertility in southern and eastern Africa.

The Importance and Characteristics of Smallholder Maize Systems

The dominant smallholder cropping systems of southern and eastern Africa are based on maize, the staple food, which accounts for about 50% of the calories consumed. Food security in resource-poor households is critically linked to the productivity and sustainability of maize-based cropping systems, which are found from sea level (the coastal zones of Mozambique and Tanzania) to elevations above 2,400 m, and from dry areas receiving less than 400 mm of rainfall (southern Zimbabwe, southern Mozambique) to well-watered areas (the higher equatorial zones). Maize accounts for 60% or more of the cropped area in Malawi, Zimbabwe, and Zambia and is almost as important in Mozambique, Tanzania, and Kenya. In Malawi, where population density in the southern region reaches an average of 215 persons per square kilometer, maize is the main crop on nearly 90% of cultivated area and contributes 80% of the daily food calories. The growing popularity of maize in Malawi has been attributed to its efficiency as a per-hectare calorie producer compared to other food plants (Carr 1994). As crop land becomes more scarce, the efficiency of calorie production per hectare assumes greater importance for farmers.

Most farm households rely on family resources, especially labor, to grow maize on 0.5-3.0 ha of land held under traditional tenure arrangements. Human labor — aided by hand-held hoes — is the predominant means of maize production across Malawi, northern and eastern Zambia, northern Mozambique, and many parts of Tanzania (Low and Waddington 1990, Waddington 1994). Elsewhere in the region, particularly southern Zambia, Botswana, and Zimbabwe, animal (mainly ox) traction is used to prepare land and help with weeding. Some farmers still grow maize in loose rotations with such crops as groundnuts and sunflowers, but increasingly maize is planted on the same land year after year, often sparsely intercropped with beans, groundnuts, cowpeas, or pumpkins. Formal intercropping is common only where human population density is high and average land holdings per family small, as in parts of southern Malawi, where each farm household has access to only about 0.8 ha.

Traditionally, African agricultural systems were largely based on extended fallows and the harvesting of nutrients stored in woody plants. The site to be cultivated was cleared by cutting and slashing plant growth and burning the dried plant material (e.g., Araki 1993, Blackie and Jones 1993, Blackie 1994). Extensive exploitation of land by a few families characterized these systems: for example, in the *chitemene* slash-and-burn system in the *miombo* woodland of northern Zambia, land was fallowed for 50-70 years, followed by cropping in the center of the clearing for a few years (Araki 1993). Today in most arable areas of Malawi, Zimbabwe, and Kenya, fallowing has almost disappeared from the agricultural system. The length of the fallow continues to decline significantly in Zambia, Mozambique, and Tanzania. Continuous maize cropping and the resulting downward spiral of soil fertility have reduced crop yields and exacerbated soil erosion (Araki 1993). In some areas, such as the wetter communal lands of northern Zimbabwe, soil is so severely depleted that without fertilizer maize will yield virtually no grain.

In many parts of Africa, including southern Africa, farmers have switched from traditional maize landraces to improved germplasm in the last 25 years. Byerlee et al. (1994) calculated that improved varieties and hybrids covered 33-50% of the maize area in Africa, but there is little evidence of greater maize productivity per hectare (CIMMYT 1992, 1994; Lele 1992). Productivity increases are disappointing even in countries where smallholders now use substantially more fertilizer (Conroy 1993). All of these circumstances emphasize the urgent need for further research on strategies for overcoming soil fertility problems. In the next section of this paper, we turn our attention to a more detailed description of the types and extent of Africa's soil fertility problems.

Overview of Soil Fertility Constraints to Maize Production

Average maize yields per unit of land have fallen in Africa partly because maize cropping has expanded into drought-prone, semiarid areas (see, for example, Gilbert et al. 1993), but a much greater negative influence on maize yield has been the loss of soil fertility, especially in wetter areas where yield potential is higher.

The old and already highly leached soils in Africa's humid and sub-humid zones have inherently low nutrient levels. Sandy and sandy loam soils derived from granite, with organic matter of less than 0.5% and very low cation exchange capacities, are widespread in Zimbabwe, southern Zambia, and western and southern Mozambique. Nitrogen deficiency is ubiquitous on these soils, while deficiencies of phosphorus (P), sulfur (S), magnesium (Mg), and zinc (Zn) are common (Grant 1981). On the sandy loam and clay loam soils in Malawi, which are chronically deficient in macronutrients, micronutrients such as S, Zn, and boron (B) are reported to be limiting at many sites (Wendt, Jones, and Itimu 1994). Zambia and Mozambique have large areas of acidic soils with free aluminum (Al^{3+}).

The largest aggregate nutrient losses in Africa are seen in major maize-producing countries with higher population densities and erosion problems. Smaling (1993) and Stoorvogel, Smaling, and Janssen (1993) estimated that annual net nutrient depletion exceeded 30 kg nitrogen (N) and 20 kg potassium (K) per hectare of arable land in Ethiopia, Kenya, Malawi, Nigeria, Rwanda, and Zimbabwe.

Buddenhagen (1992) estimated that, discounting the effects of erosion, the weathering of minerals and biological N fixation will enable, at most, 1,000 kg/ha of maize grain to be produced each year on a sustainable basis in the tropics. In hot lowland areas, such as Ghana, this equilibrium is estimated to be even lower, at 600-800 kg/ha of maize grain annually (G. Edmeades, pers. comm.). Soil loss through erosion (and soils cultivated with annual crops in the upland tropics are very prone to erosion) will reduce these yield levels considerably. Because farmers are locked into low crop productivity per unit of land from a degrading natural resource base, they will increasingly be forced to encroach on ecologically fragile environments such as the Zambezi and Luangwa Valleys, with their unique ecosystems and remnant habitats for several endangered large mammals, and on the many hilly areas where loss of protective vegetation will quickly lead to severe erosion.

These bleak circumstances are exacerbated by three limitations to change that are endemic in sub-Saharan Africa: the low use of inorganic fertilizer, declining soil organic matter, and insufficient attention to crop nutrient studies.

Low use of inorganic fertilizer

In most parts of the world, chemical fertilizers play a major role in maintaining or increasing soil fertility, but farmers in sub-Saharan Africa use very little chemical fertilizer. The FAO (1988) has estimated that the average fertilizer application in sub-Saharan Africa is 7 kg of fertilizer nutrients per hectare of arable land plus permanent crops per year. More recent calculations for 1993 by Heisey and Mwangi (1995), using similar criteria, give an average of 10 kg of fertilizer nutrients per hectare. Chemical fertilizer use is higher in some countries of southern Africa (notably Zimbabwe, Zambia, and Malawi) where the commercial farming sector is relatively well developed and fertilizer-responsive maize an important crop. Fertilizer application rates on maize have been calculated at 70 kg fertilizer nutrients per hectare of maize crop per year in Zambia, 55 kg in Zimbabwe, and 26 kg in Malawi (Heisey and Mwangi 1995). Nevertheless, these levels are well below crop and soil maintenance requirements and are likely to remain so, because fertilizer is probably the most costly cash input used by smallholders in southern Africa.

Aside from its cost, fertilizer is not used more widely because fertilizer recommendations are frequently unattractive to smallholders. Recommendations often ignore soil and climatic variation in the areas farmed by smallholders, are incompatible with smallholders' resources, or are simply inefficient. All of these shortcomings lead farmers who do apply fertilizer to incur unnecessary expense. For example, in Zimbabwe farmers are instructed to apply basal fertilizer for maize in the planting hole at planting, but instead farmers almost always apply fertilizer just after crop emergence, which is easier, less risky, and results in a negligible loss of yield under farm conditions (Shumba 1989). This practice allows farmers, after a given rain, to plant more area more quickly (important on a drying sandy soil), get better crop emergence, and make more labor available for other operations. Another example of an inappropriate recommendation has to do with the type of fertilizer recommended. There is rarely a response to K on the granite soils predominant in smallholder farming areas of Zimbabwe (Mashiringwani 1983, Hikwa and Mukurumbira 1995), yet the recommended compound fertilizer contains K as well as N and P. A better option might be to apply cheaper N alone, just after planting, and cheaper forms of P at other times.

Even when fertilizer is used, the efficiency of its use on farmers' fields (measured by the grain yield response to the addition of chemical N and P fertilizers) is often poor, which reduces the profitability of fertilizer use. Jones and Wendt (1995), summarizing data from farmers' fields in Malawi and Zambia, calculated that farmers using current fertilizer practices can expect just 9.5-16 kg of maize grain per kilogram of nutrient applied to local unimproved maize and 17-19 kg of maize grain per kilogram of nutrient applied to hybrids. Research on farms in Malawi shows that, at farmers' levels of fertilizer application, improved timing and application methods can raise the response of unimproved maize to nitrogen from 15 to 20 kg grain per kilogram of N applied and raise the response of hybrid maize from 17.4 to 25 kg grain. Furthermore, this improvement in fertilizer-use efficiency would substantially outweigh any feasible changes in fertilizer or maize prices in making fertilizer more attractive to smallholders (HIID 1994). One example of the limited profitability of inorganic fertilizer has been reported by Conroy and Kumwenda (1995); they note value:cost ratios in Malawi of 1.8 for fertilizer on hybrid maize and 1.3 on unimproved maize for moving from zero fertilizer to current recommended levels.

Declines in soil organic matter

In the tropics, the maintenance and management of soil organic matter (SOM) are central to sustaining soil fertility on smallholder farms (Swift and Woomer 1993, Woomer et al. 1994). In low-input agricultural systems in the tropics, SOM helps retain mineral nutrients (N, S, micronutrients) in the soil and make them available to plants in small amounts over many years as SOM is mineralized. In addition, SOM increases soil flora and fauna (associated with soil aggregation, improved infiltration of water and reduced soil erosion), complexes toxic Al and manganese (Mn) ions (leading to better rooting), increases the buffering capacity on low-activity clay soils, and increases water-holding capacity (Woomer et al. 1994). Current SOM inputs are insufficient to maintain organic matter levels in tropical agricultural soils.

Continuous cropping, with its associated tillage practices, provokes an initial rapid decline in SOM, which then stabilizes at a low level (for example, see Woomer et al. 1994).

The conventional mechanisms for addressing losses of SOM in tropical, rainfed, low-input systems are fallowing, rotations (especially involving legumes), the addition of animal manures, forms of intercropping (including intercropping with hedgerow legumes), and reduced tillage.[1] In southern Africa, agricultural intensification is often associated with the diminished availability of animal manures. As pressure on arable land rises, cropping encroaches on areas previously used for grazing, and livestock production becomes more difficult. This problem is more common in the unimodal rainfall areas of southern Africa, where the long dry season makes zero-grazing techniques difficult or impossible for smallholders, than in the bimodal rainfall areas of eastern Africa. Manure from cattle and other animals is very important for most farmers in Zimbabwe, less so in Zambia, but rarely available in Malawi (where animals are scarce). But even in the best areas, the supply (and, as important, the quality) of animal manure is inadequate to maintain soil fertility on its own.

Where animals are few, farmers have turned to other sources of SOM. Leaf litter from trees can make significant contributions in areas close to woodlands, but as population grows, the deforestation associated with the demand for arable land, building material, and fuel works against this option. Although composted crop residues are used in wetter areas and where crop biomass production is relatively high, composts are rarely sufficient for more than a modest part of the cultivated area, and, like manures, their quality is often poor. These technologies require substantial labor from farmers (for examples from Zimbabwe, see Huchu and Sithole, 1994, and Carter 1993). The reality is that organic matter is rarely sufficient to maintain SOM, and in marginal areas where rainfall is low it is impossible to grow enough biomass to maintain SOM. Furthermore, the productivity boost that smallholders need cannot be supplied by organic manures alone. The use of manures will need to be combined with the judicious use of chemical fertilizers, improved pest and weed management techniques, and the use of high-yielding crop varieties.

Insufficient attention to crop nutrition studies

In Africa, the research agenda has been biased away from crop nutrition studies and towards the gains that may be obtained through plant breeding. This bias is a legacy of the Green Revolution in Asia, which succeeded through the use of improved germplasm under very different conditions — particularly Asia's more fertile and uniform soils — than those prevailing in Africa. Improved maize materials can make better use of available nutrients, but in the absence of added nutrients, the gains from genetic improvement alone are small. Under low N conditions, maize scavenges the N available in the soil very effectively, and little N is left for the plant to take up by flowering (G. Edmeades, pers. comm.). For example, results from an extensive program of on-farm demonstrations over four seasons in the major maize-growing areas of Malawi showed that on relatively fertile soils and under good management, hybrids without fertilizer yielded just 1.4 t/ha compared with 0.9 t/ha for unimproved maize (Jones and

[1] Some of these techniques are used in temperate agriculture, but farmers in temperate areas still rely more heavily on purchased inputs.

Wendt 1995; Conroy and Kumwenda 1995; Zambezi, Kumwenda, and Jones 1993). In Africa, the challenge of increasing productivity without compromising sustainability is so large that farmers will need to combine gains from improved germplasm with complementary improvements in their management of soil fertility. The central issue is how to build up and maintain soil fertility under the income and, increasingly, land and labor constraints faced by smallholders.

Essentially two approaches can be used in managing soil fertility (Sanchez 1995). The best known approach, used in producing most of the world's food, involves overcoming soil constraints to meeting plant requirements through the application of purchased inputs. In fact, much of the increase in crop yields in developing countries since the Green Revolution, especially in Latin America and Asia, can be attributed to the purchased inputs used by greater numbers of farmers (Pinstrup-Andersen 1994). The second approach relies more on biological processes to optimize nutrient cycling, minimize the use of external inputs, and maximize the efficiency of input use. Our understanding of the principles underlying this second, more complex approach is not well developed, and knowledge gained in temperate areas may be inappropriate for smallholder agriculture in the tropics. These two approaches, and a more sustainable, practicable middle way that combines the best features of both, will be discussed throughout this paper as we examine practicable alternatives for smallholders.

Improved Soil Fertility and Productivity: Practicable Options for Farmers

The strong contribution of better management practices to sustaining and increasing productivity is highlighted in Figure 1. Figure 1 presents three scenarios, based on "best bet" estimates of technology adoption for Malawi, in which a maize deficit or surplus is calculated based upon the balance between maize production and consumption in a given year. Assumptions include a population growth rate of 3.2% per year; per capita annual maize consumption of 230 kg; and a constant maize area of 1.4 million hectares,[2] 20% of which is planted to improved maize at the start of each scenario. Calculations are based on national average yields of hybrid and unimproved maize for 1982-92 (these data include fertilized and unfertilized fields) (Ministry of Agriculture Crop Estimates,

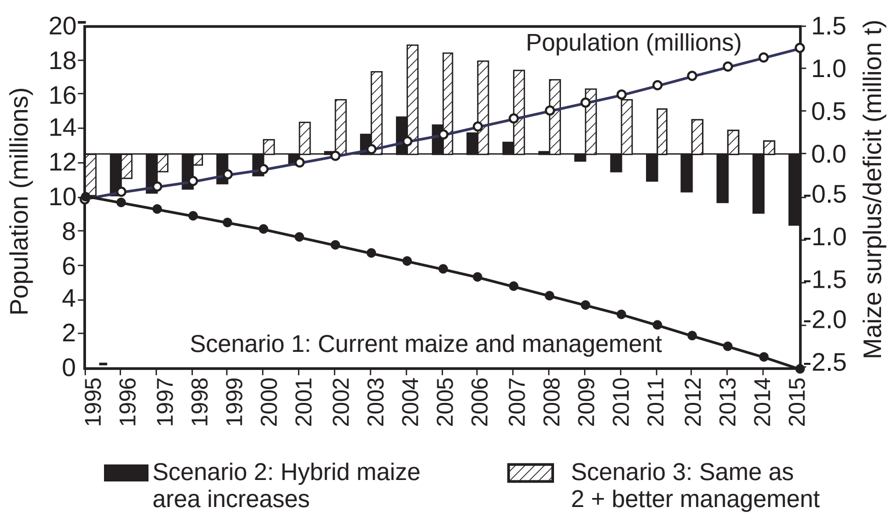

Figure 1. Malawi maize production scenarios for 1995-2015.

[2] Virtually all of the arable land available to smallholders in Malawi is under continuous maize cultivation, so the opportunities for an expansion of maize area are limited.

quoted by Conroy 1993). In all scenarios, the yield of unimproved maize is 1,000 kg/ha.

Under scenario one, the yield of improved maize is held constant at 2,500 kg/ha and the area planted to improved maize does not change. This scenario represents a continuation of the *status quo* in Malawi, where a widening deficit between national maize production and consumption is already apparent. Under scenario two, the adoption of hybrid maize increases by 20% (compounded) each year, but hybrid yields remain at 2,500 kg/ha because there is little change in soil fertility or other management practices. Under this scenario, maize production shows a modest surplus by 2002 but lapses back into a deficit just six years later. Finally, under scenario three the adoption of hybrid maize (as in scenario two) is combined with the gains in efficiency achieved from better fertilizer management by farmers of about 44%[3] and with other likely management improvements, particularly timely weeding (Kabambe and Kumwenda 1995). A yield increase of 68% is assumed when farmers use this set of improved management practices with their hybrid maize. Under this scenario large surpluses are achieved to 2015. Projected declines in the rate of human population growth make it likely that grain surpluses could be maintained even beyond 2015. Productivity improvements would thus make a difference well into the 21st century.

Although there is little argument about the need for more sustainable soil fertility management, there is less clarity on how it might be achieved. In a major overview of past impacts and future prospects for maize research in sub-Saharan Africa, Byerlee et al. (1994) contrasted farmers' high level of adoption of improved maize against the relative lack of technology for maintaining soil fertility and increasing labor productivity. Many resource management technologies are potentially available, but few are actually easy for farmers to adopt. To understand why this is so, we must look more closely at the circumstances under which increasing numbers of smallholders in Africa operate. Then we will review technologies for enhancing soil fertility to suggest how they might be made more attractive to farmers. We then proceed to outline, based on examples from practice, improvements in technology development and transfer that would facilitate smallholders' adoption of better soil fertility management practices.

Smallholder diversity, cash and labor constraints, and soil fertility management

The smallholder farm sector is characterized by considerable variability in individual access to land (in quality and quantity), resources, and skills. Literacy and numeracy are poor. The population involved in agriculture ranges from small-scale commercial farmers, through progressive farmers, to the vast majority of poorer people who endeavor to subsist, with varying levels of success, in hostile ecologies where the sustainability of life, livelihood, and environment is threatened.

The lack of cash is a dominant influence on the choices farmers make. The two major costs faced by smallholders in producing maize are labor and fertilizer. Labor may be provided by the family, it may be bought in from other farmers, and it may be sold to others for food or cash. Often the farm household is headed by a woman, who has small children. Older children may be at school or may have moved to town. If the woman is fortunate, her husband and the children who live away from home will still help support the rural

[3] See the earlier section of this paper, "Low use of inorganic fertilizer."

household through cash or kind. If they do not, she must attempt to support herself and her children from what she can grow or sell. She will be living on a piece of land that has been cultivated many times before, whose inherent fertility has long been exhausted. Weeds will have established themselves and will compete strongly for light, water, and nutrients with whatever she plants.

Given a hectare or more of land, the woman may be self-sufficient in food if her health is good and the weather favorable. But at the start of the rains people often suffer from malaria and diarrhea, and illness of the farmer or her children will delay planting. If the rainy season is poor (and "Africa" and "drought" have become nearly synonymous to many), her crop may fail. The odds are that in some years, often in many, she will not produce enough food for her family's needs. This failure will require her to work for neighboring farmers who will then feed or pay her (and any children who work with her) for labor. While she plants, weeds, or fertilizes the neighbor's crop, her own is left unplanted, unweeded, and unfertilized until later in the season. Late planting and poor weeding lead to a poor harvest, and once again the farmer will find herself without food before the next crop comes in.

This is the cycle that the next maize revolution has to break. Increasing numbers of rural families in Africa cannot produce sufficient food for their annual needs (Weber et al. 1988). Malawi offers a view of what the future could look like for many more Africans unless current trends are reversed: in Malawi some 60% of rural households (41% of the total population) produce less than they require to feed themselves through the year. The amount of cash such a household needs to buy inorganic fertilizer far exceeds its total annual cash income (HIID 1994).

Clearly, African smallholders, almost wherever they live, face conditions of difficulty and stress for which both tradition and science have few real answers. Although technically sound solutions to many of their problems exist, all too often these solutions turn out to be financially or managerially unsound. Nevertheless, some solutions may prove feasible for smallholders.

Increasing fertilizer use and fertilizer-use efficiency

Increasing the number of smallholders using fertilizers — Since the 1960s, fertilizer use has been growing in sub-Saharan Africa at around 6.7% annually (Heisey and Mwangi 1995), but many farmers still do not use fertilizers, which will remain a high-cost item for the foreseeable future. The base of fertilizer users cannot be consolidated and expanded without generating better returns from fertilizer through increased efficiencies in its use. Much greater use will also need to be made of organic sources of fertility to improve fertility management and reduce cost. How can current fertilizer users, and those who are likely to be able to afford some fertilizer, achieve increases in fertilizer-use efficiency? A three-pronged strategy is envisaged, in which:

- the type of inorganic fertilizer and its use are carefully tailored to the conditions faced by smallholders;
- the proportion of locally produced organic materials is increased, which will not only reduce the cash cost of fertilizer but increase the efficiency of inorganic fertilizer use; and
- agronomic and economic factors receive greater consideration when breeding priorities are established for maize and legumes, so future improved materials fit smallholders' circumstances.

**Increasing inorganic fertilizer-use efficiency — ** A central part of any strategy for expanding the number of smallholders who use inorganic fertilizer will be to determine how to make the best use of the limited amounts of fertilizer that a typical smallholder is able to purchase. Increasing fertilizer-use efficiency will require a significant shift in thinking for both researchers and policy makers in Africa. For instance, Zimbabwe has a fifty-year history of agricultural research on inorganic fertilizers, but much of this work was geared towards users who could afford relatively large quantities of fertilizer (the large commercial farms and growers of cash crops). Since Independence in 1980, a great deal of work has examined the appropriateness of types, amounts, timing, and placement of inorganic fertilizers for food crops produced by smallholders,[4] yet recommendations for inorganic fertilizer have not given sufficient attention to the cash constraints and the risk faced by resource-poor farmers in marginal areas. Of the 32% of farmers in Zimbabwe who followed the fertilizer recommendations for their maize crop in the near-average season of 1990/91, 48% failed to recover the value of the fertilizer (Page and Chonyera 1994).

Additions of soil micronutrients can improve the yield response to macronutrients (N and P) on deficient soils. Nutrients such as Zn, B, S, and Mg can often be included relatively cheaply in existing fertilizer blends; when targeted to deficient soils, these nutrients can dramatically improve fertilizer-use efficiency and crop profitability. During the 1950s, 1960s, and 1970s, 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 micronutrients 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, Jones, and Itimu 1994).[5]

There is evidence that the most promising route to improving inorganic fertilizer efficiency in smallholder cropping systems is by adding small amounts of high-quality organic matter to tropical soils (Ladd and Amato 1985; Snapp 1995). High-quality organic manures (possessing a narrow C/N ratio and a low percentage of lignin) provide readily available N, energy (carbon), and nutrients to the soil ecosystem, and they build soil fertility and structure over the long term. Their use will increase soil microbial activity and nutrient cycling and reduce nutrient loss from leaching and denitrification (De Ruiter et al. 1993; Doran et al. 1987; Granastein et al. 1987; Snapp 1995).

Two long-term cropping studies in Kenya and Nigeria indicate that organic plus inorganic inputs sustain fertility at a higher level than the expected additive effects of either input by itself (Dennison 1961). Nutrient effects alone do not explain the benefits derived from modest amounts of organic manure combined with inorganic fertilizers. High-quality carbon and nitrogen provide substrate to support an active soil microbial community. Soil microbes are valuable not so much because they supply nutrients directly, but because they enhance the synchrony of plant nutrient demand with soil supply by reducing large pools of free nutrients (and consequent nutrient losses from the system).

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4 See Grant (1981), Metelerkamp (1988), and a recent summary by Hikwa and Mukurumbira (1995).

5 For details, see “A case study in applied research,” later in this paper.

Thus microbes maintain a buffered, actively cycled nutrient supply (De Ruiter et al. 1993; Snapp 1995). Research is now generating examples of yield gains available on farmers' fields in southern Africa through inorganic/organic combinations (Table 1 gives three recent examples). Often the largest gains are seen on research stations where soil fertility is already high. On-farm gains are usually lower because of inherently low soil fertility, water deficits, and management compromises, but this practice is still worthwhile. Many farmers already recognize these effects and combine, where possible, small amounts of high-quality organic inputs with inorganic nutrients.

Increasing the availability and use of organic sources of fertility

As noted earlier, the organic inputs available to most smallholders are rarely sufficient to maintain SOM, and more organic materials must be introduced rapidly into smallholders' cropping systems. Options include rotations, green manures, animal manures, intercropping, strip cropping, relay cropping, and agroforestry.

The role of legumes — Most of the promising routes to increased SOM involve legumes, which have been the focus of well-meaning efforts to transform smallholder African agriculture since the turn of the century.

Table 1. Examples of gains in maize yield obtained through combinations of organic and inorganic fertilizer at levels practicable on farmers' fields, Malawi and Zimbabwe

			Maize grain yield (t/ha)				Yield of combination as a percentage of alone treatments
Organic fertilizer	Inorganic fertilizer	Location and season	No fertilizer	Organic alone	Inorganic alone	Organic + inorganic combination	
Leucaena leucocephala alley cropped with maize; 1.5-2.5 t/ha Leucaena prunings applied to maize	30 kg N/ha applied to maize crop	Chitedze Research Station, Malawi, 1988-90	2.24	3.32	2.72	3.60	119
Pigeonpea intercopped with maize in previous season; pigeonpea residues incorporated into the soil	48 kg N/ha applied to maize crop	Luyangwa Research Station, Malawi, 1993-95	0.87	1.70	1.98	2.31	126
Cattle manure: 13-25 t/ha broadcast and plowed in before planting	112 kg N, 17 kg P, and 16 kg K/ha as split basal and topdress applications	6 communal farms, Wedza and Chinyika, Zimbabwe, 1994/95 season (a drought year)	0.79	1.11	1.30	1.93	160

Note: These gains are from the first cropping season after fertilizer application. Additional gains can be expected in following seasons.

The efforts of Alvord in Zimbabwe are typical of the genre. Green manures were heavily researched from the 1920s to 1940s (Metelerkamp 1988), and large-scale commercial farmers used green manures widely until the real price of inorganic fertilizers fell in the 1950s and green manuring became uneconomic. However, rising real prices of inorganic fertilizers and concern over the sustainability of current cropping systems have once again attracted interest in green manures (see Hikwa and Mukurumbira 1995).

Annual legumes are used as sole crops in rotation with cereals, are intercropped, or are occasionally used as green manures. Perennial legumes are sometimes retained in farmers' fields and are just beginning to be incorporated as hedgerow intercrop or alley crop systems. Giller, McDonagh, and Cadisch (1994) conclude that biological N fixation from legumes can sustain tropical agriculture at moderate levels of output, often double those currently achieved. Under favorable conditions, green manure crops generate large amounts of organic matter and can accumulate 100-200 kg N/ha in 100-150 days in the tropics.

Legumes remain marginal in many of the maize-based systems of the region, however, for several reasons. Low P levels in the soils inhibit legume growth, and so at a minimum P must be added. Much of the work underlying legume-based technologies has been done on research stations. Insufficient account has been taken of the need to tailor these technologies to farming circumstances where labor is in short supply. The fertilizer needed to "kick start" the system may be too costly or unavailable, and there are often difficulties in obtaining legume seeds (e.g., Giller, McDonagh, and Cadisch 1994). Finally, the family may not be able to release land from staple food crops.

There is often a direct conflict between the need to assure today's food supply and the need to assure tomorrow's food supply by building up soil fertility over a long period. Farmers discount the value of a benefit that will only be achieved several years from when investments are made. The most suitable legumes, from the soil fertility perspective, are often the most difficult for the farmer to adopt. Broadly speaking, the larger the soil fertility benefit from a legume technology is likely to be, the larger the initial investment required in labor and land, and the fewer short-term food benefits it has.

Grain legumes. Grain legumes have the fewest adoption problems and are widely grown by farmers, mainly for home consumption of the seed and sometimes leaves. However, the more productive (high harvest index) grain legumes add relatively little organic matter and N to the soil, since much of the above-ground dry matter and almost all the N is removed from the field in the grain (see Giller, McDonagh, and Cadisch 1994). Species that combine some grain with high root biomass and shoot-leaf biomass, such as pigeonpeas (*Cajanus cajan)* and dolichos beans (*Dolichos lablab*), offer a useful compromise of promoting farmer adoption and improving soil fertility (K.E. Giller, pers. comm.).

Carr (1994) reports that, on severely depleted soils in Malawi, soybeans (*Glycine max*) will produce more calories per unit of land than unfertilized maize, in addition to fixing N from the atmosphere. Also in Malawi, Kumwenda (1995) reported average soybean yields of 2,200 and 860 kg/ha, respectively, in monoculture and intercropping from a self-nodulating (promiscuous) variety, Magoye. Promiscuous soybeans are attractive to smallholders because they do not have to be inoculated with *Rhizobium* spp. bacteria to fix N, and they also have good root and above-ground biomass. Magoye is grown very widely in Zambia and is now grown by thousands of smallholders in Malawi, but Malawi has not yet approved recommendations for its use. Zimbabwe does little soybean research for smallholders. The bias in regional soybean development is towards varieties with high grain yields, which are favored by large-scale producers whose interest in soil fertility improvement is secondary.

Legume intercropping. Intercropping, in which two or more crops are grown mixed together on the same ground for all or most of their life cycle, is a widespread, traditional African agricultural practice (Andrews and Kassam 1976). Legumes in intercropping systems can contribute some residual nitrogen to the subsequent crop (Willey 1979). However, low-growing legumes are often shaded by taller cereals (Dalal 1974, Chang and Shibles 1985, Manson, Leughner, and Vorst 1986), and under smallholder management in low-fertility conditions, poor emergence and growth of the intercropped legume is common. This limits the N and organic matter contribution of the legume on farmers' fields to levels well below the potentials found on research stations (Kumwenda et al. 1993, Kumwenda 1995).

One of the more promising intercrops is late-maturing pigeonpea. Even though early growth of the legume is reduced when it is intercropped with maize, pigeonpea compensates by continuing to grow after the maize harvest and produces large quantities of biomass (Sakala, 1994). In Malawi, Sakala (1994) reported a pigeonpea dry matter yield of 3 t/ha from leaf litter and flowers when pigeonpea was intercropped with maize. Pigeonpea is easily intercropped with cereals and, even if the seed is harvested for food, the leaf fall is sufficient to make a significant contribution to N accumulation. The disadvantage is that pigeonpea is highly attractive to livestock and impractical to grow where livestock are left to roam the fields freely after harvest, a common practice in many African smallholder systems.

The importance of intercrops in densely populated regions is widely recognized. Intercrops have a stabilizing effect on food security and enhance the efficiency of land use. However, in semiarid areas, plant densities (and thus potential yield per hectare) must be reduced in intercropping systems (Shumba, Dhliwayo, and Mukoko 1990). Those authors, working in southern Zimbabwe, found that cowpea-maize intercrops greatly reduced the grain yield of maize in dry years. Natarajan and Shumba (1990), reviewing intercropping research in Zimbabwe, observed that cereal-legume rotations appear to offer greater prospects of raising the yield of cereals than do intercrops. Whereas maize benefits from being grown *after* groundnuts (*Arachis hypogaea*), maize-groundnut intercrops often reduce maize yield (see Hikwa and Mukurumbira 1995). Cowpea-maize (*Vigna unguiculata*) intercrops yield better than either maize or cowpea sole crops on a land-equivalent basis in wetter areas of Zimbabwe (Mariga 1990).

Legume rotations. Legume rotations are an important practice for restoring soil fertility on larger land holdings. Rotations allow crops with different rooting patterns to use the soil sequentially, reduce pests and diseases harmful to crops, and sustain the productivity of the cropping system. The amount of N returned from legume rotations depends on whether the legume is harvested for seed, used for forage, or incorporated as a green manure. In Malawi, MacColl (1989) estimated net N of 23-110 kg/ha from pigeonpeas, 23-50 kg/ha from dolichos beans, and 25 kg/ha from groundnuts.

In Nigeria, Jones (1974) and Giri and De (1980) estimated 60 kg N/ha from groundnuts.

The yield response of a cereal crop following a legume can be substantial. In Malawi, MacColl (1989) showed that the grain yield of the first maize crop following pigeonpea averaged 2.8 t/ha higher than the yield of continuous maize that received 35 kg N/ha each year. Mukurumbira (1985) showed large maize yields in Zimbabwe following groundnuts and bambara nuts (*Voandzeia subterranea*), without supplemental inorganic nitrogen. Similar studies in Tanzania by Temu (1982) found that maize yields after sunnhemp (*Crotolaria* spp.) were 3.65 t/ha when residues were removed and 4.82 t/ha when they were incorporated. The incorporated residues were equivalent to an application of 80 kg N/ha from inorganic fertilizer. Supplementing sunnhemp green manure by incorporating 40 kg N/ha gave a yield of 6.83 t/ha, which was equivalent to an application of 160 kg/ha of inorganic N fertilizer.

Improved fallowing with legumes. Natural short fallowing of overworked land in Zimbabwe results in little or no increase in soil fertility (Grant 1981). Improved fallows, using *Sesbania sesban* as a way of adding significant amounts of N and organic matter to soil, have been evaluated in Eastern Province, Zambia, where short, two- to three-year fallows are common. On the research station, maize yielded between 3 and 6 t/ha of grain for each of four years following a two-year improved fallow, compared to a yield of 1-2 t/ha in the unfertilized control (Kwesiga and Coe 1994). From these data, Place, Mwanza, and Kwesiga (1995) calculated that when inorganic fertilizer is not used — the common practice in eastern Zambia since fertilizer subsidies were removed — it is profitable for farmers to invest in the improved fallow. The use of improved fallows avoids the competition effect between trees and crops (Kwesiga and Coe 1994). But where land is limiting, the feasibility of improved fallow systems remains unproven.

Agroforestry. Agroforestry refers to land-use systems in which woody perennials (such as trees and shrubs) are grown in association with herbaceous plants (such as crops or pastures) and/or livestock in a spatial arrangement, a rotation, or both, and in which ecological and economic interactions occur between the trees and other components of the system (Young 1989). Given the widespread decline in soil fertility, the use of leguminous, multipurpose trees for improving soil fertility has been a major thrust of agroforestry research in the region.

Alley cropping, sometimes referred to as hedgerow intercropping, was developed in the late 1970s at the International Institute of Tropical Agriculture (IITA) and is the best-known agroforestry system developed for improving soil fertility (Kang, Reynolds, and Attah-Krah 1990). The underlying assumption of this technology is that moisture and nutrients below the roots of annual crops will be used by the more deeply rooted tree crop. The tree crop is pruned to supply nutrients to the soil, which are used by the shallowly rooted annuals. Jones et al. (1996), Wendt et al. (1996), and Bunderson et al. (1991) showed that the application of *Leucaena leucocephala* leaf prunings in an alley cropping system raised maize grain yield and increased soil pH; organic C; total N; S; and exchangeable calcium (Ca), Mg, and K.

Important aspects of agroforestry are problematic, however. Inorganic P may be needed to realize increased maize yields. Leucaena (the most widely researched hedgerow species) suffers from susceptibility to termite attack at the seedling stage, severe defoliation by the recently arrived Leucaena Psyllid, and poor biomass production under low fertility and on low pH soils. Saka et al. (1995) have estimated that the cost of producing N from Leuceana biomass is comparable to that from inorganic sources. The technology is labor intensive and management sensitive. Trees and associated crops can compete for moisture, nutrients, and light (Mbekeani 1991, Ong 1994). Observations suggest that competition for soil moisture is particularly acute at the beginning of the rainy season before moisture reserves have built up. Without a better understanding of the competitive effects between trees and associated crops, especially those effects below ground, the potential of alley cropping is unproven at the farm level.

Some progress has been made on aspects of these problems. Research has identified alternative species that are better adapted and produce more biomass than *L. leucocephala* (Bunderson 1994). *Gliricidia sepium* and *Senna spectabilis* have both shown potential to produce more biomass in a wider range of ecologies.

Another agroforestry technology that may offer some promise is *Faidherbia albida*, a vigorous leguminous tree long used by African farmers for improving crop yields where the tree is naturally abundant. The species has the characteristic, unique among African savanna tree species, of retaining its leaves in the dry season and shedding them at the onset of the rains. The resultant fine mulch of leaf litter decomposes rapidly, enriching the topsoil in plant nutrients and organic matter. Saka et al. (1994) have described how natural stands of the tree have been used in maize production systems in Malawi. Although farmers recognize the value of *F. albida*, the tree has not been integrated systematically into maize-growing areas.

Cereal residues and animal manure — The burning of crop residues remains common. Where it is a deliberate farmer practice (mainly in areas with few livestock), burning is used to release nutrients quickly, ease land preparation, and reduce pest and disease pressure. Although the nutrient content of maize stover is relatively low, stover can contribute to the productivity of the soil. Such residues must be managed carefully, however, because N can be immobilized at the time of peak maize N requirements, resulting in poor crop growth (Nandwa, Anderson, and Seward 1995); this fact is well known to farmers.

In unimodal rainfall areas where stover tends to break down slowly in the soil, and on sandy soils where soil N is very low, maize stover is usually fed to livestock. As well as keeping animals alive, this practice helps cycle residues in a way that makes them more beneficial to the crop. In smallholder areas where cattle are common, as in parts of Zimbabwe, farmers often apply cattle manure to fields that will be planted to maize. Losses of N from such systems are often high, however. Cattle manure is applied in a dried, aerobically decomposed form, often with a high sand content and an N content that is frequently less than 1.2% (Mugwira and Mukurumbira 1984). Manure is broadcast and plowed into the soil before planting. Survey discussions with farmers and informal assessments indicate that farmers apply around 8-20 t/ha every three to five years (Mugwira and Shumba 1986). Research shows that the most efficient use of manure is to combine it with some inorganic fertilizer (Murwira 1994). This is a common practice of farmers. Station-placement or dribbling into the planting furrow, rather than broadcast application, are promising ways of increasing the crop yield benefits from cattle manure (e.g., Munguri, Mariga, and Chivinge 1996).

Improving maize genotypes for soils with low fertility

In addition to finding ways of altering the soil to better support maize crops, researchers are also developing maize genotypes that perform better when soil fertility is limiting. A slight improvement of N-use efficiency has been reported in tropical maize, with prospects of further gains (Lafitte and Edmeades 1994a, 1994b). At CIMMYT in Mexico, three cycles of full-sib recurrent selection for grain yield under low soil N, while maintaining grain yield under high soil N, were conducted in a lowland tropical population, Across 8328 (Lafitte and Edmeades 1994a, 1994b). This resulted in a per-cycle increase in grain yield under low N of 75 kg/ha (2.8%), with similar yield improvements under high N (Lafitte and Edmeades 1994b). If these improvements continue over another three to five cycles of selection, they will be substantial. At CIMMYT in Zimbabwe, similar work in population ZM609, adapted to midaltitude areas of southern and eastern Africa, led to large initial gains in N-use efficiency (Short and Edmeades 1991), but recent work has been inconclusive (Pixley 1995).

Also, significant progress in using full-sib recurrent selection to develop tropical maize for tolerance to high Al^{3+} saturation in acidic soils is reported by Granados, Pandey, and Ceballos (1993). These materials should be tested and modified to suit African conditions, and breeding work should be established to develop maize that yields well in soils that have high concentrations of H^{+} but without Al^{3+} or Mn^{2+} toxicity. Breeding for tolerance to micronutrient deficiencies may be another worthwhile long-term goal.

Agronomists and social scientists continue to have a role in encouraging breeders to persevere with work on soil fertility issues. Most breeders are more comfortable with breeding to overcome biotic constraints, where they feel they can make more progress. However, the edaphic constraints found on smallholders' fields need to be addressed. There is an urgent need for improved germplasm adapted to nutrient deficiencies and other edaphic stresses. Most of the gains achieved in N-use efficiency through breeding have come from improved N utilization to produce more biomass and grain yield with no increase in total N uptake (Lafitte and Edmeades 1994b). Nevertheless, there is some concern that future genotypes bred for low soil fertility may gain their advantage from extracting more micro- and macronutrients from the soil. The outcome of such a strategy is uncertain, and therefore it is important not to rely solely on crop improvement.

The way forward

The technologies needed to manage soil fertility in southern Africa do not differ from those developed for other parts of the world. Inorganic fertilizers are a key element of fertility management, because the need for added external nutrient inputs is inescapable, but such fertilizers should not be the sole source of nutrients. Some sources of organic fertility, mainly based around the use of legumes in the cropping system, can usefully complement inorganic fertilizers. However, important practical questions about both sources of fertility under smallholders' circumstances remain unanswered: the optimum use of small amounts of inorganic fertilizers, the best combinations of organic and inorganic fertilizers, how to produce sufficient amounts of organic manures under low-fertility conditions, the best management compromises in the use of labor between critical seasonal tasks, and adjusting fertility management according to seasonal rainfall and other external factors. This deficiency of information persists despite some adaptive research on these issues in the 1980s and early 1990s (e.g., Waddington 1994).

Yet these are the very questions that smallholders seek to answer. Typically, farmers are looking for means of combining these inputs and employing them in ways that minimize the requirements for additional cash, labor, and land. Little past or ongoing experimentation exists to guide them through the choices, and extension offers little counsel.

From the previous discussion, it is clear that flexible soil fertility recommendations are required that better address actual nutrient deficiencies, take advantage of cropping system opportunities, are efficient under the highly variable rainfall regime faced by most smallholders, and are compatible with farmers' socioeconomic circumstances. Combinations of technologies (involving organic and inorganic sources), often with each component employed suboptimally, will be needed. Organic manures are highly variable and usually in short supply. Mixing high-quality organic sources with inorganic fertilizer can substantially improve nutrient-use efficiency and crop productivity. The resultant practices will be practicable and profitable, and thus candidates for wider adoption.

Transferring experience in fertility management from other regions of the world requires not only adaptation but also a much greater understanding of the processes through which fertility can be managed under African conditions. This concurrent requirement for adaptive research as well as basic process research is taken up in the next section of this paper.

Linking Adaptive and Process Research to Improve Technology Development and Dissemination

African crop management research requires two critical types of research to be conducted in a collaborative, highly focused manner:

- basic process research for a better understanding of the soil fertility cycle (its inputs and its losses) on African farms, to ensure that technology will be effective, and
- adaptive research with farmers and other clients, to ensure that an integrated sequence of activities follows up on findings from basic research.

The methods for each type of research are different. It is rare for scientists working in process research to have a full grasp of the skills needed for adaptive research, and *vice versa*. Fertility changes have long-term effects on productivity, but it is important to remember that changes in agriculture are typically incremental rather than spectacular. Only through a consistent, long-term effort will scientists understand the changes that are taking place. To ensure that the research agenda remains fixed on important productivity problems and does not get sidetracked into equally challenging but less relevant avenues, these researchers must share a common vision of the problems faced by farmers.

Many of the key characteristics of adaptive agricultural research are well described in the literature (for example, see Tripp 1992). We propose to build on the foundation of adaptive research by adding a long-term perspective, in which investigation, review, and interaction with producers and other concerned parties elicit a coherent research strategy running consistently over time. The next section provides one example of such a process, which is already underway. We then proceed to show how progress in applied research requires an underpinning of high-quality, carefully prioritized basic studies.

A case study in applied research: Overcoming micronutrient deficiencies for maize in Malawi[6]

Research on the relief of micronutrient deficiencies for maize in Malawi exemplifies the commitment needed for "successful" soil fertility research. Over three seasons from 1990 to 1992, Conroy (1993) showed that smallholders following current fertilizer recommendations — a single blanket recommendation of 92 kg N and 40 kg P_2O_5 per hectare was standard throughout Malawi — obtained only about 3 t/ha of maize grain, even though farmers planted hybrids with yield potentials exceeding 10 t/ha. More than 40% of the smallholders who applied fertilizer at recommended rates failed to cover the cost of fertilizer application.

Table 2 shows the research sequence and outputs. The process embraced soil chemical analysis, investigative trials with missing micronutrients at a relatively small number of

Table 2. The relief of micronutrient deficiencies on maize in Malawi: an example of a long-term research process

1987 - 89	1989 - 90	1990 - 91	1991 - 92	1992 - 93	1993 - 94	1994 - 95 and onwards
Activities and methods						
* Review past trials and conduct farm surveys	* Missing nutrient trials at 10 on-farm and research station sites in selected areas * Soil and tissue chemical analysis at sites			* Nutrient supplement treatments to on-farm demonstrations * Soil analysis at 400 sites in Central Malawi	* Map regional nutrient deficiencies * Formulate new basal fertilizers and distribute * Collect and analyze soil from 3,000 geo-referenced sites throughout Malawi * Verification trials of new fertilizers at several hundred on-farm sites, involving farmers	* Use GIS to map sites * Better target verifications to sites deficient in S and Zn, involve extension and farmers * N response trials at sites where micronutrient deficiencies satisfied
Key outputs						
* Micronutrient deficiency likely cause of yields <3 t/ha with current N-P-K recommendation	* Regional deficiencies of S, Zn, B, and K found * Yields increase by 40% over standard N-P when micronutrient deficiencies satisfied * P not needed at some sites while others need more than current recommendation * More verification with farmers needed			* Near universal S and Zn deficiency in some ADDs * Confirmed yield responses * Optichem to produce 20:20:5+4S +0.1Zn and 15:10:5+4S+0.1Zn	* Good yield response to basal fertilizers containing S * Responses at low-Zn sites were poor; 0.1Zn is insufficient	* Optichem to produce compound fertilizer with 1Zn * Include results from better targeted verifications in new recommendations * Results from response economics * Results from N response trials where micronutrients relieved
Organizations						
* Maize and Soils Commodity Research Teams in the Department of Agricultural Research, Ministry of Agriculture →						
* Smallholder farmers →						
		*FAO/Ministry of Agriculture/UNDP project				
				*Fertilizer maker (Optichem) →		
					*Ministry of Agriculture Extension Service →	

Note: ADDs = Agricultural Development Divisions; GIS= geographic information system; FAO = Food and Agriculture Organization; UNDP = United Nations Development Programme.

[6] The work synthesized here is the result of efforts by many persons and organizations in Malawi. In particular, credit for much of this research goes to John Wendt and Richard Jones, Rockefeller Foundation Post-doctoral Scientists attached to the Department of Agricultural Research in Malawi from 1989 to 1993.

on-farm sites, and the formulation of new fertilizer blends (including Zn and S) with a fertilizer manufacturer. This last step was combined with simple on-farm verifications of increased yield and profitability when the new formulations were used. The on-farm verifications actively involved the extension service and farmers.

In 1987, informal farmer surveys indicated that low yields were not generally caused by poor planting or weeding or adverse climatic conditions. Farmers had been growing maize continuously (sometimes with a minor legume intercrop) with minimal rotation for many years. Researchers hypothesized that low yields might result from deficiencies of nutrients other than N and P. Two initial research goals were identified:

- to determine yield response, in a given soil type and agroecological zone, to fertilizers that addressed local soil nutrient deficiencies; and
- to determine the relationship of soil fertility analytical values to maize yield response to fertilizer added (this relationship is influenced by climate, soil type, and profile).

The literature and other sources of information established that the absence of one or more of a range of nutrients (besides N and P) had the potential to depress yields significantly. Several of these potential nutrient deficiencies were discarded and not researched: either the deficiency was unlikely, was already addressed in the existing fertilizer formulation, or was impractical to deal with in the Malawian context.

In 1989, researchers initiated a series of on-farm trials to evaluate deficiencies of N, P, K, S, Zn, and B at several sites throughout Malawi. A "missing nutrient, minus one" trial design was used to evaluate the relative contribution of each nutrient to maximizing yields. To keep the clients' needs sharply in focus, researchers conducted much of their work in smallholders' fields. New methods included tissue sampling, in which ear leaves were taken from all plots at silking and analyzed for N, P, Ca, Mg, K, S, Zn, Cu (copper), Mn, Fe (iron), and B. Data from the soil and plant analyses were correlated with yield data to determine minimum soil analytical criteria for the elements studied.

There was a regular process of review. The treatments and treatment methods evolved from year to year, based on experience from previous years. By 1991/92, a general review concluded that yield data indicated regional deficiencies of B, Zn, S, and K. In deficient regions, average yields improved by 40% over yields obtained using the existing N and P application when the deficiencies were satisfied. Lime applications were necessary at some sites. Soil and plant analyses showed P application was unnecessary at some sites, while at other sites the recommended P fertilizer rate was insufficient.

To refine these observations, the research team collaborated with a fertilizer demonstration project run by the extension service and FAO. In 1992/93, micronutrient supplement treatments were added on selected extension fertilizer demonstrations throughout the country. An analysis of soil samples from 400 smallholder sites enabled researchers to develop preliminary maps of areas with S, Zn, K, Cu, and P deficiencies for maize in Malawi (Wendt, Jones, and Itimu 1994).

The next step was to work with a local fertilizer company to produce practical fertilizer blends that addressed these regional deficiencies. Two types of fertilizers were produced in 1993/94; in 1994/95, based on further experience, another formulation was produced. Concurrently, the characterization of nutrient deficiencies was greatly expanded to refine the nutrient deficiency maps. More than 3,000 soil samples were collected and analyzed for pH, P, Ca, K, Mg, Zn, Cu, B, soil organic matter, and soil texture. The sample locations were geo-referenced (elevation, longitude, and latitude) to develop a computer database that could be used with a geographic information system (GIS). Farm management information was also collected. Trials were conducted from 1993/94 onwards to verify the new fertilizer formulations under farmers' conditions and demonstrate more efficient methods for using fertilizer. This work was done in conjunction with the extension service, with guidance and assistance from the Department of Agricultural Research. In 1994/95, work was started to define new response curves for N and P with hybrid maize where the micronutrients were added. The fertilizer company has advertised the new 20:20:5+4S+0.1Zn fertilizer and procedures are in place to incorporate new fertilizers into standard recommendations.

Clearly blanket fertilizer recommendations are inadequate. They result in the inefficient use of an expensive, usually imported, commodity, which is costly for the farmer and for the nation. This is uncontroversial, but progress in dealing with this evident and crucial problem has been slow. This example from Malawi illustrates how progress is possible with modest resources but a clear sense of direction. Researchers exploited the potential of modern fertilizer blending systems to produce small "runs" of fertilizer to given specifications. Through a focused program of research and verification, fertilizer recommendations can be developed for localized areas at a surprisingly reasonable cost, and through database management techniques, these recommendations can be refined further.

Basic process research

The challenge and the tools — The applied research outlined in the preceding section must be underpinned by high-quality research aimed at comprehending the basic processes underlying nutrient flows in tropical soils. Nutrient budgets and process-level research track the consequences of crop management strategies in smallholder farming systems. The goal is to synthesize our knowledge of processes involved in nutrient cycling efficiency, which will enable us to predict which agronomic technologies enhance yield potential over the long term. The challenge is enormous, because detectable changes in soil organic matter and other soil fertility parameters occur very slowly. For example, in a hedgerow intercrop trial at Bunda College of Agriculture, University of Malawi, soil organic C was not altered after 10 years of widely differing residue input rates (Snapp and Materechera 1995).

The first step towards further improving organic matter technologies is to quantify nutrient losses and inputs at different scales and extrapolate among them. Typical scales include the plot level, the farm level, the watershed level, and the regional level (Fresco and Kroonenberg 1992). The definitive test for evaluating the effects of technologies on soil fertility is the measurement of yields over the long term. Studies conducted over decades in a systematic, rigorous manner are clearly needed in sub-Saharan Africa and for the tropics generally. However, because farmers need improved technologies now, faster methods are required. Regional assessments of soil nutrient status and losses have necessarily been almost entirely based on extrapolation of plot estimates (Smaling 1993), but results have not been reliable.

Several new methods hold considerable promise for assessing nutrient flows across the heterogeneous landscape of smallholder farms in the tropics (Barrios, Buresch, and Sprent 1994; Jones, Snapp, and Phombeya 1996; Parton 1992; Snapp, Phombeya, and Materechera 1995). Powerful tools of the trade include nutrient monitoring, new methods in soil analysis, modeling, and networked or chrono-sequence trials to allow rapid insight into soil fertility processes (Anderson and Ingram 1993; Jackson et al. 1988; Parton 1992; Snapp, Phombeya, and Materechera 1995). Investigations must be conducted on representative sites of well-characterized agroecosystems. Networked trials and standardized analytical methods are needed to quantify the consequences of different management regimes for the soil resource base (Anderson and Ingram 1993). This type of basic research could potentially support a major shift in tropical agronomy from empirical testing to designing crop management strategies. To be successful, this research requires a continuing commitment to building bridges among fields such as agronomy, ecology, soil biology, chemistry, and physics.

Nutrient budgeting — Nutrient budgeting can be used to develop improved ways of using available nutrients. We have underlined the importance of organic matter management on Africa's leached and depleted soils. Using conventional methods from temperate zones, it is difficult to maintain SOM. Substantial amounts of organic inputs are needed to enhance SOM in tropical cropping systems (Jenkinson 1981). Recent findings suggest that small additions of high-quality organic material can increase nutrient cycling efficiency. Such material is high in available N and provides a source of energy (available carbon) to soil microorganisms. Enhanced activity of soil microbes can increase nutrient turnover rates, improving nutrient availability to crops while minimizing nutrient losses from leaching and volatilization (De Ruiter et al. 1993; Doran et al. 1987; Granastein et al. 1987; Ladd and Amato 1985).

These findings suggest an opportunity in the tropics to use active microorganism populations to buffer (or reduce nutrient losses from) low-input cropping systems. Although the pool of inorganic nutrients is small in such systems, the nutrient supply may be sufficient to support crop growth because of the continual re-supply of nutrients by microbially mediated turnover rates. Nutrient losses due to leaching and volatilization are reduced (Figure 2). Crop nutrient budget methodology (after Jackson et al. 1988), focusing on N losses (N is the nutrient most limiting to growth, and most vulnerable to losses from smallholder farms in southern and eastern Africa), is being developed to test this theory.

Related process studies have recently been initiated in Malawi, including ^{15}N isotope labeling, to quantify the effects of small amounts of organic residues applied with inorganic nutrients under field conditions (Jones, Snapp, and Phombeya 1996). Researchers in Zimbabwe have undertaken a range of intensive studies of N efficiency, using ^{15}N isotope and novel N monitoring techniques (TSBF 1995, Tagwira 1995). While the results from these studies remain preliminary, the initial findings are exciting.

Development of new methods — New techniques have recently been developed for separating SOM into fractions that may be biologically meaningful and that appear to have predictive value for agronomists and land managers. Physically based isolation of SOM fractions can be achieved rapidly and easily by sieving soil and separating SOM on the basis of size (Cambardella and Elliot 1994, Christensen 1992). Early findings are that a fraction of SOM known as the light/large (LL) fraction provides a good indicator of active SOM.

Use of SOM fractionation, and measurement of LL-associated organic C and N, are being evaluated in Zimbabwe, Kenya, and Malawi (Barrios, Buresh, and Sprent 1994; Okalebo, Gathua, and Woomer 1993; Snapp, Phombeya, and Materechera 1995). Organic C in the LL fraction was higher in two Malawian soils amended with *G. sepium* or *L. leucocephala* compared to a control (continuous maize with no fertilizer) or an intercrop with a legume that does not fix N, *S. spectabilis* (Saka et al. 1995).

Root studies — Roots play an important role in regulating nutrient cycling efficiency. A vigorous, effective crop rooting system is essential for efficient nutrient acquisition, particularly for mobile nutrients such as nitrate N. Nitrogen losses from tropical cropping systems have not been well documented but are expected to be substantial, exceeding 30-70% of N inputs. Major N losses are thought to occur early in the cropping season as a result of high initial mineralization rates, inorganic N accumulation during the dry season, and limited root growth of young crop plants (Myers et al. 1994).

Understanding root behavior is also essential to minimize competition associated with intercropping technologies. Several important agroforestry systems are based on the assumption that the trees reduce nutrient losses by scavenging nutrients at a depth lower than the crop roots (Young 1989). Preliminary findings from studies of two significant maize/perennial legume intercrop systems for Malawi

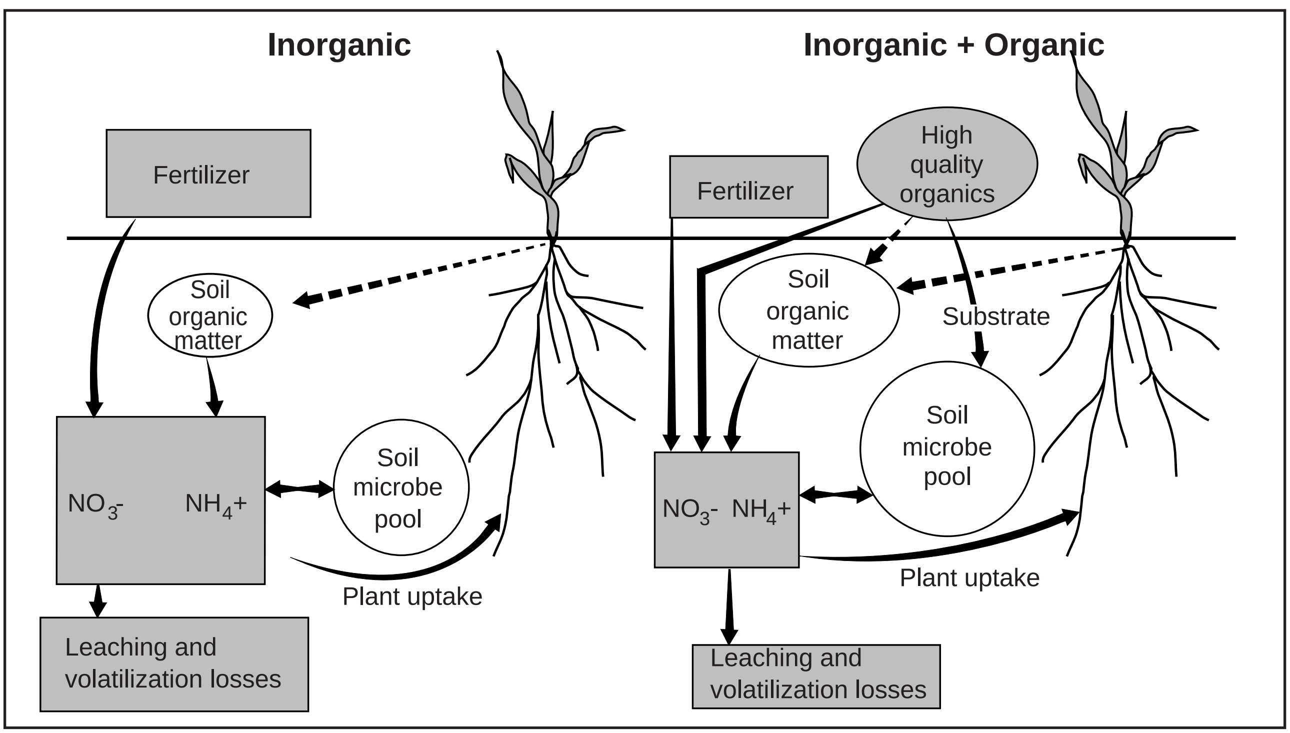

Figure 2. The role of high-quality organic inputs in improving the efficiency of inorganic fertilizer use.

Note: Rapid cycling between inorganic N and soil microbe N allows the plant to take up N without a large pool of inorganic N, which is vulnerable to leaching.

— *S. spectabilis* and *G. sepium* alley cropped with maize — suggested that ridge planting of maize (a widespread practice of Malawian smallholders) reduced competition between maize and the perennial legumes (O. Itimu and K.E. Giller, pers. comm.). However, the data strongly pointed to intense competition between crop and tree roots and to only modestly deep rooting of the perennials. The soil environment influenced rooting patterns to as great a degree as genotype. Thus reducing negative interactions between tree roots and annual crops, and enhancing benefits from tree roots, may be fundamental to the success of the technology (Giller, Itimu, and Masamba 1996).

Nutrient release synchrony — Another approach advocated for increasing nutrient cycling efficiency is to synchronize nutrient release with crop demand (Anderson and Ingram 1993). Synchronizing the release of nutrients from organic materials with a crop's requirement for nutrients can increase nutrient cycling efficiency (Myers et al. 1994). This central hypothesis of the Tropical Soil Biology and Fertility Program (TSBF) suggests that organic inputs of varying quality can be used to manipulate nutrient supply. Laboratory incubation studies have shown that high-quality residues (e.g., narrow C/N ratio, low percent lignin) supplied in conjunction with low-quality residues (e.g., wide C/N ratio and/or high lignins) can provide a continuous nutrient supply, with N being released from high-quality residues first (O. Itimu and K.E. Giller, pers. comm., 1995; Snapp, Phombeya, and Materechera 1995; TSBF 1995). Preliminary field data support these findings. For three out of four Malawi soils, levels of inorganic N were enhanced in soil amended with high-quality *G. sepium* residues, compared to controls (no fertilizer or organic inputs) or to soil amended with moderately high quality residues of *S. spectabilis* (Snapp, Phombeya, and Materechera 1995). Nevertheless, synchronizing nutrient release with nutrient demand using organic residues is technically demanding. Just how practicable this is for farmers on their fields every year has yet to be shown.

The quality of residues is difficult to evaluate. The SOM fractionation methods discussed earlier may provide one means of assessing the quality of residue after it is incorporated into soil; most important, these methods may also serve to quantify the consequences for soil quality. Preliminary indications are that plants with high lignins, polyphenolics, and other anti-quality factors may not release nutrients for many growing seasons, and thus these residues may be undesirable to use as organic soil amendments (Myers et al. 1994). Studies have been initiated in Zimbabwe and Malawi to test the synchrony hypothesis under field conditions (TSBF 1995, Snapp and Materecha 1995).

Conclusion — We have emphasized ways in which types of technologies (organic and inorganic sources of soil fertility) and types of research (adaptive and basic process research) must be linked to ensure that more rapid progress is made in developing soil fertility practices that smallholders can adopt. Now we focus on another set of important links in technology development: the interactions between soil fertility technologies and other inputs and management factors in the cropping system.

Exploiting Interactions of Soil Fertility Technologies with Other Inputs and Management Factors

In southern Africa, the defining feature of the ecology is the dry season, which lasts seven to eight months. Because the dry season is so long, important farm operations, particularly planting, weeding, and fertilizing, are concentrated in the critical early weeks of the rainy season. The options for addressing soil fertility problems are influenced by crop choices, the season, the climate, and a host of other factors, some of which farmers can control or modify, and some of which they cannot. Thus it is the interaction of soil fertility technology with other, possibly more readily adoptable, farmer inputs and management practices that needs particular consideration. Interactions can be expected with weed control practices, with moisture availability, with fertilizer-responsive and -efficient maize, with labor, and with draft power.

Interactions with weed management

Kabambe and Kumwenda (1995) examined the interaction between weed growth and fertilizer-use efficiency in Malawi. They found that farmers who weeded twice at the critical periods for maize achieved a higher yield, with half the amount of fertilizer, than farmers who weeded only once (Figure 3).

Where animal draft power is available, the options for exploring interactions with weed management methods increase (see Low and Waddington 1990). Results from Zambia show that combining basal and topdress fertilizer, applied when weeding 20-cm-tall maize, resulted in a savings of six person-days per hectare during the peak demand period for family labor. The practice also gave a 19% yield increase compared with the standard farmer practice of a basal application just after planting, followed by late weeding and topdressings (Low and Waddington 1990; 1991). These results were developed into separate recommendations for ox-cultivators and for farmers who used hand hoes for weeding. Ox-cultivators were advised to weed with oxen two weeks after emergence while covering the mixed basal and topdress fertilizer (applied immediately beforehand) in the same operation; hand weeding on the crop row within the subsequent two weeks was also recommended. Hand-hoe weeders were advised to combine the first hoe-weeding with a mixed basal and topdress fertilizer application, beginning ten days after emergence. A second weeding would follow two weeks later.

Soil fertility decline may cause weeds (and insect pests and diseases) to build up and thereby indirectly affect crop production. A well-known example of such an interaction is the parasitic weed, *Striga* spp., which tends to build up when soils are depleted, although once it is established it is hard to control through improved soil fertility alone. Data

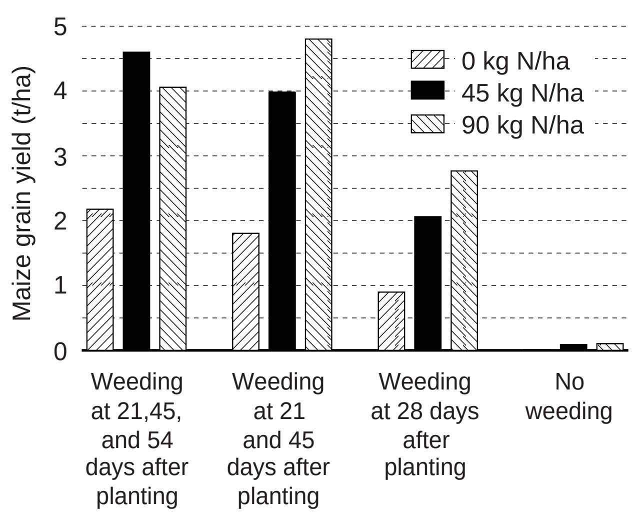

Figure 3. Effect of weeding frequency and N application on maize grain yield.
Source: Kabambe and Kumwenda (1995).

from long-term trials in Kenya have shown that incorporated crop residues play an important role in reducing Striga parasitism (Odhiambo and Ransom 1995).

Interactions with moisture

The climate of southern Africa means that lack of moisture frequently constrains maize yields and yield response to fertilizer. The efficiency (measured through grain production) of both water use and N use is raised when both water and N are in adequate supply. But the high risk of poor response to fertilizer in dry years is a major reason why most farmers in semiarid areas use little or no fertilizer. An overdependence (as in Zimbabwe) on developing site-specific fertilizer recommendations through soil chemical analyses alone (Grant 1981, Metelerkamp 1988), and the concept of regular maintenance dressings (for K and P), have resulted in unrealistically high and rarely adopted recommendations for smallholder farms, especially in semiarid areas. Uncertainty exists over appropriate N-P-K fertilizer recommendations for semiarid areas. The utility and economics of fixed recommendations for such areas is increasingly questioned (e.g., Mataruka, Makombe, and Low 1990; Shumba et al. 1990; Piha 1993; Page and Chonyera 1994).

The practices of smallholders in Zimbabwe reflect the need for substantially revised fertilizer recommendations. The frequency with which these farmers apply inorganic fertilizer and the amounts they apply are strongly influenced by seasonal rainfall. Almost all smallholder farmers apply some inorganic fertilizer to maize in the wetter areas (Natural Regions II and III). In a survey of ten communal lands in such areas, Waddington et al. (1991) found that farmers applied an average of 65 kg N/ha to their earlier plantings of maize. But for late plantings (of lower yield potential), N rates fell to about 60% of those for earlier plantings. In semiarid areas, the use of inorganic fertilizer is low. Rohrbach (1988) found that in Chivi Communal Area of Zimbabwe (which is representative of these conditions), fewer than 10% of farmers regularly applied fertilizer (usually low rates of topdress N). Data from the 1991-94 seasons in Gutu (Natural Region IV) Communal Area show 80% of farmers using an average of 19 kg N/ha on fields that were monitored. In Chivi (Natural Region IV-V), only 23% of farmers applied fertilizer at an average rate of 8 kg N/ha (DR&SS/CIMMYT, unpublished). In intermediate rainfall areas such as Shurugwi-Chiwundura and Wedza, most farmers (79-91%) use topdress N but fewer than half applied basal fertilizer (Huchu and Sithole 1994).

A partial solution for overcoming the excessive risk that constrains fertilizer use in dry areas can be found in "response farming" techniques (Stewart and Kashasha 1984, Stewart 1991), which use early rainfall events to decide on the amounts of fertilizer to apply. Piha (1993) explored the interaction between nutrient use and rainfall in Zimbabwe. Trials over five years on farmers' fields showed that when farmers adjusted fertilizer use to the evolving rainfall pattern in any one season, they obtained 25-42% more yield and 21-41% more profit than when they followed existing fertilizer recommendations. Piha also showed that existing recommendations were too risky for lower rainfall areas and needed to be adjusted downwards to be profitable.

Such techniques can be refined by using crop simulation models to predict outcomes under variable water and N conditions. When these models are used in conjunction with GIS, the resulting information can be used to delineate target agroecological areas or groups of farmers for which a particular input level is appropriate (e.g., Dent and Thornton 1988; Keating, Wafula, and Watiki 1992). Keating, Godwin, and Watiki (1991), using a version of the CERES maize simulation model modified for Kenya, quantified the economic risks associated with N application for Machakos and Kitui Districts. The risk of economic loss from fertilizer application clearly rose as crop available moisture declined.

The significance of the recent work by Piha (1993) and similar efforts (Stewart and Kashasha 1984, Stewart 1991) is that the judicious use of inorganic fertilizers can make productive and profitable agriculture reliably possible on the poor soils and in the semiarid conditions that characterize the environments where many of Africa's smallholders live.

Institutional Change in Research and Development Organizations

The development and adoption of soil management technologies for smallholders ultimately depends on the capacity of many groups of people in many countries to interact in new, more productive ways. How will research and development organizations need to adapt to ensure that Africa's soil fertility problems are dealt with successfully? What shifts in perspective are necessary for research and extension to accommodate the great diversity among smallholders? What institutional changes are needed to support productivity increases in the small-farm sector? In the sections that follow, we propose some answers to these questions.

Addressing smallholder diversity

Research and development organizations will have to find better ways of addressing the variability in the smallholder farming community. If these organizations are to establish affordable programs that can address the many different problems involved, they will need to carefully and thoughtfully characterize the population into strata of coherent and useful size (see Blackie, 1995, for an example of stratification in this context). There are several ways in which knowledge of the characteristics of different strata might be exploited to improve the impact of new technologies. Two ways are explored here.

Enhanced farm management advice — There is no single route to improved maize productivity for African farmers. In the "developed" world, farmers have been guided in the use of new and expensive technologies by carefully formulated farm management advice. Such counsel is rarely available to African farmers. Although the cost of having highly qualified farm management advisors readily available to all African farmers is clearly prohibitive, so too are the costs (both social and economic) of accepting the continuing decline in African farm productivity. Through joint ventures with donors and with private sector input suppliers, farm management advice can be made available to farmers already using inputs and to farmers whose efficiency can be improved so as to make input use profitable.

Note that the emphasis in providing better farm management advice moves from making inputs "affordable" (usually by providing inputs in a subsidized form, with all the inherent problems and contradictions of subsidies) to making them profitable. The emphasis also changes from the diagnostic (typified by efforts in farming systems research and various forms of rapid rural appraisal) and the prescriptive (ranging from top-down extension efforts to the Training and Visit system favored by the World Bank) to a problem-solving format in which the farmer is actively involved. Such a format will feature recommendations that are conditional on circumstances and include "if-and-then" decision making. It provides a framework for effective research/extension linkages and helps create a technology development process that is driven by smallholders' needs.

Improving productivity for farmers with the fewest resources — Particular attention needs to be paid to the agricultural production problems of the farmers with the fewest resources — typically farmers who do not reliably feed themselves and their families year on year. This group is analogous to the long-term unemployed who occupy the welfare rolls of the developed world (and remain an intractable problem for those better endowed countries). It includes the old, the work-shy, the handicapped, and many single mothers and widows. Their numbers may be substantial (as high as 40% of the smallholder population in Malawi) and are growing. The poverty trap faced by the poorest families precludes their active participation, under present circumstances, in a market economy (except as distress sellers of labor and, sometimes, food). Both equity and reason indicate that they should not be ignored — although in fact they *are* ignored by the conventional technology development and extension process.

Cash crops can play an important role in priming the soil fertility input pump by bringing extra cash income to farmers, but options for very poor farmers may be few. In Malawi, for example, burley tobacco may be the only crop that farmers can grow on their tiny holdings to generate sufficient cash for purchasing inputs (Carr 1994). But in many situations it is unrealistic to expect sophisticated and possibly risky cash cropping to provide the first step to a better life for this group of farmers. They are desperately short of cash, cannot afford the luxury of experimentation, and often lack the confidence and ability to deal unaided with many aspects of commercialization. Moreover, cash cropping depends on reliable, honest markets for inputs and outputs, and targeted production advice on a new commodity is essential for farmers.

Credit is often proposed as a solution but is of value only to individuals who are periodically short of cash to purchase inputs. Farmers who are chronically short of cash need alternative solutions. In some richer African countries, the informal financial sector (which commonly includes such groups as Savings Clubs and Rotating Savings and Credit Associations) can be quite large. Clubs designed and operated by smallholders meet their special needs for financial services. In Malawi, where individual savings are minute, an innovative effort using a combination of start-up grants and savings mobilization has been remarkably successful in reaching the poorest farmers around Dowa in central Malawi (VEZA project). It has introduced them to improved maize technologies, quickly moving farmers to financial viability. Savings rather than credit, therefore, provide the mechanism for introducing cash-poor smallholders to improved technologies (Chimedza 1993). The conventional wisdom holds that most households in the smallholder sector have a low marginal propensity to save, and therefore are not able to invest from savings. Experience has shown that the capacity to save is rather larger than typically assumed, which gives an important leverage point when dealing with rural poverty. A sound macroeconomic policy that maintains low monetary inflation is important to support such efforts.

Institutional change to support smallholder productivity increases

The successful implementation of the technology development and transfer processes outlined in this paper requires the commitment of substantial resources over extended periods. While the private sector and non-governmental organizations (NGOs) will be essential partners in this effort, high-quality public sector research and extension will remain a critical element of the process (see Blackie, 1994, for a discussion of the role of the private sector). The inadequate funding base of most public national agricultural research systems (NARSs) in Africa means that these institutions face high staff turnover. The scientists who remain often suffer from low morale, caused by poor financial incentives as well as the lack of resources for undertaking research. Hence the NARSs, on their own, are ill equipped to take on the difficult task of maintaining institutional memory.

The system for developing agricultural technology in Africa is not well adapted to comprehending and responding to the long-term problems of the continent. Institutional memory is limited. Inadequate budgets (and the poor use of the funds that are available) lead to a collection of short-lived, disparate research projects which rarely "follow through" to the farmer. For plant breeding research, the international agricultural research system has been able to address these deficiencies to some extent; the results are apparent in the uptake of improved germplasm. Structures for maintaining the institutional memory for germplasm development are comparatively well developed. The international agricultural research centers (IARCs) have a long, successful history of assisting NARSs in producing improved varieties by drawing on international experience of varietal development. The IARCs maintain a comprehensive set of data on varietal characteristics, on breeding environments, and on pest and disease pressures. A process of collaboration and training with national research scientists has been established and is used extensively by plant breeders in developing countries.

By contrast, the effort to maintain a similar corpus of knowledge on crop management is minuscule. The role of agronomists and social scientists in the international research community is more poorly defined than that of plant breeders. Their numbers and influence are substantially less. The research vision and agenda for crop management have largely been left in the hands of the NARSs, a choice justified by the belief that crop management issues are location specific and do not lend themselves to the kind of broad support that has proved so useful in crop breeding. Possibly this belief derives from the initial successes of the Green Revolution in Asia, where national scientists took up broadly adapted improved germplasm and incorporated it into improved productivity packages. But in the highly variable ecologies and farming communities of Africa, ignoring management factors avoids the heart of the problem. The continuing underinvestment in the development of high-quality crop management technology over the long term has compromised the research community's ability to answer the real problems facing African smallholders. Some effective ways of organizing an increased commitment follow.

Crop management research is typically reported in a highly distilled format in the form of farmer recommendations, which suffer from two important flaws. The first flaw, which has been mentioned earlier and is well documented in the literature, is that recommendations rarely take the diversity of farmers' circumstances into account.

The second is that, because of their highly distilled nature, recommendations are not a good repository for information over the long term. The data from which the recommendations are derived may be lost long before the recommendation itself is discarded. Progress in soil fertility management will require information to be retrieved and shared efficiently among those concerned with promoting and developing improved technologies. Recent advances in computer databases make this task easier. Given the small size and limited capacity of many African research and extension services, obvious opportunities will arise from regional collaboration. Some efforts in this direction have already been made (a recent example is SACCAR, the Southern African Center for Cooperation in Agricultural Research and Training) but have failed to realize their potential.

The needed impacts from soil fertility work will be obtained through a long-term commitment to research and extension by interdisciplinary, interinstitutional, and intercountry groups of staff that include not only technical scientists but also social scientists, extensionists, the private sector, and NGO staff. Opportunities need to be created for these people to work more closely on common topics and trials. A climate of mutual review and constructive criticism is essential. Financial constraints mean no single country or institution can bring sufficient resources to bear on these widespread, complex issues. There is a clear need for continuity in resources focused on soil fertility improvement, efficiencies from regional cooperation in the use of those resources, and better regional access to results. One way of developing a more integrated approach is through formal networks.

A variety of networks related to soil fertility research are working at several levels. The most important process-orientated soil fertility research network in Africa is AfNet, run by the TSBF Program. AfNet brings together African scientists to work on improving the synchronization of soil nutrient supply to nutrient demand by the crop, through site characterization and the use of common methods (e.g., Seward 1995). A good example of a more applied soil fertility research and extension network is the network established in late 1994 by the Rockefeller Foundation with the Malawian and Zimbabwean national research and extension programs and CIMMYT. This network emphasizes joint research priority setting, planning, and integration through meetings and peer review; research on high-priority issues, including network trials across maize-based agroecologies; information exchange and training for network scientists; and the distribution and use of research results and other information through enhanced interaction between the farmer, extension, and research (Waddington 1995).

These networks overcome some of the negative attributes of previous networking efforts; they are internally driven by the participating scientists rather than externally driven by donors. But this is not a sufficient condition for success in addressing client needs. We need to move even further to networks that take the lead on integrating farmers, NGOs, extension services, and policy makers with research in the testing and dissemination of appropriate soil fertility technology. Without this kind of concerted action, many countries in sub-Saharan Africa will suffer from a weakening natural resource base and a continuing decline in the standard of living, especially among people who depend on agriculture.

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