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THE PROBLEM OF MAINTAINING SOIL FERTILITY IN EASTERN KENYA: A REVIEW OF RELEVANT RESEARCH

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The Australian Centre for International Agricultural Research (ACIAR) supported collaborative research with the Kenya Agricultural Research Institute (KARI) in Machakos and Kitui Districts between 1984 and 1993. Drs Simpson and Okalebo were collaborators in that research, affiliated with ACIAR and KARI respectively. Dr Lubulwa is a Senior Economist with ACIAR in Canberra.

PURPOSE OF THE REVIEW

THIS REVIEW TRACES THE HISTORY and progress of research in eastern Africa into the problems of maintaining soil fertility and sustainable productivity on the croplands, with particular reference to the 'medium potential' areas of the 'moist savanna'. These are the areas of medium but unreliable rainfall (average 600–800 mm/year). They span the FAO (Food and Agriculture Organization) classifications of 'semi-arid' and into the less-favoured end of the adjacent 'sub-humid'. The review deals mainly with studies in eastern Kenya, but also calls on reports from other areas of eastern and southern Africa with related agricultural systems, and where similar problems of maintaining soil fertility are experienced.

As an example of the problem, the present study centres on the situation in Machakos District, Kenya, where population and agricultural production have increased some sixfold during the years 1930–1990. In this 'medium potential' area, intensification of agriculture, with two crops taken every year, puts heavy pressure on the soil resource. Tiffen and colleagues (1994) described the excellent progress that has been made in reducing soil erosion by contour banks and terracing, especially in the higher rainfall hill areas of Machakos. While they recognised that soil fertility has declined, these authors suggested no feasible and comprehensive solution to this increasingly important problem. They did not mention that the conservation of soil and water has, by increasing the supply of soil moisture, actually increased the potential for the 'mining' of the remaining soil nutrients by crops. With current low nutrient inputs, this can produce short-term gains in crop yields but will aggravate the problem of maintaining soil fertility in the long term. English and co-workers (1994) also did not recognise this reality, stating (p. 35) that 'any deleterious effects of changes in the nature of the resource base *(due to cultivation and cropping)* have been more than offset by improvements due to terracing, etc., and the farmers have learned how to manage the resource base better'.

This review aims to show that progress is indeed being made towards better land management practices in districts like Machakos. Several examples are given of farmers working towards affordable techniques for better soil fertility management. However, the overall progress in soil fertility management is slow, very uneven, and is hampered by major socioeconomic hurdles. The low rates of adoption of better soil management practices, despite the conclusions of recent on-farm research and modelling, suggest that further on-farm research and extension are urgently needed. Apparently many small-scale farmers need education on their possible options, and assistance in selecting appropriate solutions. Without such effort, and enabling facilities such as financial credit and better fertilizer distribution, the improvement rate in soil fertility management in eastern Kenya is likely to remain generally low.

Some of the options in better soil fertility management for farmers with modest resources are explored in the light of recent research, and their relative economic attractions and risks surveyed.

BACKGROUND

THE RAPIDLY INCREASING populations in sub-Saharan Africa linked with low inputs of soil nutrients and increasingly intensive cropping over much of the cultivated lands have resulted in the stagnation of, then gradual decline in, per capita production of food grains over the period 1960–90 (Makken 1993a). Gerner and Harris (1993) surveyed the recent history of inorganic fertilizer consumption in sub-Saharan Africa. Average rates of fertilizer application across Africa are outstandingly low by world standards, ranging from about 1 kg/ha cropland in Central Africa to 15 kg/ha in southern Africa. These national averages disguise large variations between agro-ecological zones within countries and even between individual farmers. FAO (1993) forecasts increasing food deficits if farming practices are not improved, and estimates that food sufficiency can be achieved only if fertilizer usage rises to 90 kg/ha by the year 2010 and 160 kg/ha by 2030.

Total inorganic fertilizer usage in sub-Saharan Africa during 1992 was about 1.28 million tonnes (Gerner and Harris 1993). Kenya and Tanzania used roughly equal amounts, and together accounted for some 100 000 tonnes of this total. Consumption during 1975–90 had been growing at 3.4% annually, overall; in East Africa the rate was nearly 5%; in southern Africa, 1.7%. However, structural adjustment policies of many governments have led to a stagnation in fertilizer consumption since the late 1980s. In some countries fertilizer use has been declining, e.g. in Uganda, where usage has decreased by 40–60% between 1980 and 1990 and farmers now rely heavily on local organic sources (Swift et al. 1994). It is not surprising that soil productivity is decreasing generally — apart from the relatively few cases where farmers with better financial resources are able to afford the nutrient inputs necessary for sustainable crop production.

Generally, throughout sub-Saharan Africa, the existing low-input agriculture results in depletion of the major soil nutrients nitrogen (N), phosphorus (P) and potassium (K). Overall, this depletion has been calculated at 22 kg N, 2.5 kg P and K 15 kg/ha/year (Stoorvogel et al. 1993), with much higher values for Kenya. The extent of the problem varies both within national boundaries and on national scales, depending on the inherent soil fertility and the intensity of cropping imposed. Annual nutrient losses are particularly acute in the densely populated highland areas of Ethiopia, Kenya, Rwanda, Burundi, Malawi and Lesotho (Smaling 1993). For these countries, even national average cropland losses are calculated to exceed 40 kg N, 6 kg P and K 15 kg/ha/year.

In the densely populated, heavily cropped district of Kisii, SW Kenya, aggregated nutrient losses were calculated at 112 kg N, 3 kg P and K 70 kg/ha/year, with some serious P deficiencies.

EARLY SOIL FERTILITY RESEARCH

CABI (1994) recently reviewed soil fertility research in East Africa (1930–1990) and published an annotated bibiliography with over 1000 abstracts.

Early soil fertility work, starting soon after 1930, was largely concerned with the effectiveness of vegetative fallows, combined with animal manure applications, designed to restore fertility after a period of cropping. This work was in the context of a gradual demise of shifting cultivation, as communities became more settled and populations increased (Padwick 1983). A major long-term fertility experiment in Eastern Uganda at Serere Research Station, started in 1936, was designed to establish what ratios of time under crop to time under fallow, supplemented by varied inputs of manure, could produce sustainable crop yields. The experiment continued for at least 25 years (i.e. five of its rotational cycles). The results were reviewed by Jameson and Kerkham (1960), Mills (1960) and McWalter and Wimble (1976). Essentially, the experiment showed that the beneficial effects of resting from cropping under a grass/bush fallow could be largely (not entirely) replaced by the application of manure once in each 5-year rotation, but would require application rates greater than 5 t/ha.

Later work (Simpson 1961; Stephens 1967) at Kawanda, near Kampala, showed that the beneficial effects of resting fallows of deep-rooted grasses, e.g. *Chloris gayana* and *Pennisetum purpureum*, were due largely to the capture of leached nitrate and bases, particularly K, from the subsoil and the return of these nutrients to the surface as increased organic N and associated exchangeable cations. The physical effects on soil structure and rainfall acceptance, which had previously been thought to be important, were found to be only short-term transient improvements.

At Katumani, Machakos, in a drier climate, Bennison and Evans (1968) found that accumulations of nitrate in the soil profile after bare fallow, legume crops or short-duration maize could have significant effects on subsequent crop yields. The size of the residual effect varied greatly with the amount of seasonal rainfall in both the first and second cropping seasons, as well as on the sequence of crops in the rotation.

Much of the early soil fertility work pointed to the importance of organic sources of nutrients in controlling nutrient availability. Typical are the studies of Birch and Friend (1956) throughout East Africa, Stiven (1972) in western Tanzania, and Foster (1969, 1981) in southern and eastern Uganda. Analyses showed a close correlation between soil organic carbon (C) content, organic N, and the availability of most other nutrients. Soil pH was also generally higher in the soils of high organic matter content. Available P was much less closely associated with organic C, and could be associated with variations in parent material, or reactions with ferric and aluminium ions in the more oxic profiles.

Concurrent with general soil fertility research were many detailed studies on the dynamics of the mineralisation of soil organic N as affected by moisture regimes. Cycles of drying and rewetting were found to greatly stimulate N mineralisation (Birch 1958, and many subsequent reports — see CABI 1994). The accumulation of nitrate near the soil surface and its movement to the lower profile by leaching during the cropping phase of rotations also captured the attention of several workers across East Africa (ap Griffith 1951; Mills 1953; Leutenegger 1956; Robinson 1960; Simpson 1960; Stephens 1962).

Studies during the 1960s also investigated the causes of soil fertility decline under continuous cropping, and the subsequent restorative processes under vegetative fallow. Probably the most significant of these was the work of Jones (1967, 1968) on ferrallitic soils in southern Uganda. It showed that large quantities of cations were leached into the subsoil, accompanying the nitrate movement previously observed, during three years of cropping at Namulonge, north of Kampala. A subsequent three years of restorative fallow under perennial grasses recaptured much of the leached nutrients, which otherwise were beyond the reach of the annual crops grown, and brought them back to the surface soil. Jones found that crop yields could be maintained in the three-year cropping phase when the fallow phase was reduced to only one year, if inorganic nutrients were applied in the amounts required to replace the nutrients lost by leaching. In this case, ground limestone had to be included to neutralise the gradual acidification of the poorly buffered soils.

These results (Jones 1967, 1968) appeared to offer the possibility of continuous cropping without the resting or fallow phase. This promoted a period of research, particularly in Uganda, on the intensive use of inorganic fertilizers on cash and basic food crops (Stephens 1969a,b). Souza Machado (1969) reported that the responses to fertilizers obtained in farmers' trials throughout eastern Uganda could be economic if farmers raised their level of husbandry, or a 50% subsidy was placed on fertilizers.

Much of the research on intensive use of fertilizers up to about 1970 (or even later in some areas of East Africa) failed to have much impact on small-scale farmers in the medium potential areas. It probably supplied useful information for large-scale farming and plantations, and assisted the adoption of hybrid maize varieties in the higher potential areas of western Kenya. During 1970–72 the area planted to hybrid maize by small-scale farmers in Kenya more than doubled to 280 000 ha, and fertilizer sales also increased by about 200%. Since then, however, fertilizer use has fallen back to about the 1969 level, largely because of economic structural adjustments and consequent instability in the fertilizer market (Gerner and Harris 1993).

The limited impact of research on small-scale farmers' methods of maintaining soil fertility up to the 1980s can be blamed partly on political factors such as continuing civil strife in Uganda in the 1970s, the unsuccessful Ujamaa movement in Tanzania, and continuing land subdivision and resettlement schemes in Kenya which released new land, of varying qualities, for cultivation.

There were other factors. Early researchers did not often stop to ask farmers their attitudes to using the advocated range of possible inputs and new practices. This was the period of 'transfer of technology' or 'top-down approach', in which social and economic realities failed to influence the course of research. The researcher was regarded as the source of all knowledge, which simply had to be conveyed to the uneducated farmer (L.H. Brown 1968, on the attitudes in Kenya circa 1945; reported in Tiffen et al. 1994, p. 252).

The 1980s brought major changes in research approaches to problems of low productivity on small-scale farms. The socioeconomic attitudes of the farm household became a prime consideration with the rise of farming systems research (FSR). The increasingly important question was why farmers are so slow to adopt the options so attractive to researchers. This question is addressed below, after a survey of the natural resources and farming systems of eastern Kenya, and some of the problems that have developed.

NATURAL RESOURCES IN EASTERN KENYA (MACHAKOS)

THE SOILS

The soils of Machakos District are typical of the plateaux of eastern Africa. They are derived from the pre-Cambrian 'basement-complex' rocks consisting mainly of granites, gneisses, and sometimes of schists, sandstones or phyllitic shales. There are volcanic influences on the periphery of the District, including the basaltic Yatta plateau, but these have little overall effect on the soils or agriculture of Machakos. The better-drained red soils are mainly Alfisols (USDA Soil Taxonomy), with varying degrees of weathering and acidification, bringing them into the luvisols, alisols, lixisols and acrisols of the FAO–UNESCO classification system. In areas of more extreme weathering and clay degradation, the soils grade into Oxisols (USDA) or ferralsols (FAO). A catena sequence, more common in central Uganda and north-eastern Tanzania, may develop on undulating landscapes where the ferralsols on the upper slopes grade into acrisols, luvisols, etc., then to poorly drained grey soils in the valleys. In some valleys, soils of vertic properties occur expanding through to wide plains of Vertisols, but such areas are often too dry for cropping and have other unique physical problems for cultivation. Alfisols occur widely through the semi-arid and subhumid regions of eastern Africa, including parts of Kenya, Tanzania, and Uganda, and much of southern Africa.

The Alfisols of eastern Kenya are generally low in organic matter (typically about 1.0% C and 0.1% N) and often are marginally to acutely deficient in P (Okalebo et al. 1992). Phosphorus availability varies greatly with parent material and cropping history. With the low rates of nutrient inputs that prevail on the great majority of small-scale farms, soil fertility usually declines markedly during continued cultivation and cropping. Soil physical properties include high erodibility, surface capping under cultivation and poor infiltration of rainfall. This has led to serious erosion and losses of soil nutrients on many of the steeper cropland sites in the past (Okwach et al. 1992; Tiffen et al. 1994). Cation exchange capacity is generally low to very low but the soils are often deep and well structured, allowing deep penetration of plant roots and a moderately good capacity to hold available water.

THE CLIMATES

Average annual rainfall distribution through central Kenya, Tanzania and Uganda suggests large areas of good agricultural potential receive more than 800 mm/year. However, this is misleading because great seasonal variations in rainfall, especially in eastern Kenya and much of Tanzania, have been described by many authors (e.g. McCown et al. 1991; Keating et al. 1992a).

In Kenya, Uganda and northern Tanzania, and also southern Ethiopia, there are two cropping seasons each year. In Kenya these are known as the long rains (March–June) and the short rains (October–January) but the timing and relative lengths of each growing period vary substantially with location. Further south, the two growing seasons merge progressively into one long wet season (November–April in Zimbabwe) with unreliable times of onset. Total rainfall generally increases with altitude and proximity to hill masses. There are, however, substantial rain shadow effects on the north-west slopes of mountains, especially near Mt Kilimanjaro and Mt Kenya.

The agro-ecological zones (AEZs) of eastern Kenya were classified by Jaetzold and Schmidt (1983). Machakos District contains hill areas (<10%) in the wetter zones 2 and 3, through drier zones 4 and 5 (about 80%) to marginally arid areas in zone 6 (10%), suitable only for rangeland or occasional drought-tolerant crops (see Figure 1). The 'semi-humid' zones 2 and 3 were originally dry forest and moist woodland, with a high climatic potential for cropping (rainfall >900 mm) and suitable for growing coffee. Zone 4 is transitional, 'semi-humid to semi-arid', with average but unreliable rainfall of 700–850 mm, and suitable for maize, cotton, sunflower and legumes. Zone 5 has high potential for livestock-raising, with average rainfall of 500–800 mm, greater seasonal variability and higher temperatures. Although much of this zone is more suitable for sorghum and millets, maize has become a popular crop. Main discussion in here centres on the problems of zones 4 and 5, which cover most of the District and resemble much of eastern and southern Africa. The main conclusions are relevant to zones 2 and 3 also.

DEMOGRAPHIC AND ECONOMIC CHANGES

Populations in Kenya and Uganda have increased fivefold to sixfold between 1930 and 1990, typical of the whole eastern African region. Within the highly productive highland areas, population densities can exceed 500/km^2, e.g. in Kisii in SW Kenya, 680/km^2 (Smaling et al. 1993). In Machakos District, population densities vary with agro-ecological zone (Jaetzold and Schmidt 1983) from 285/km^2 in AEZs 2 and 3, to 110/km^2 in AEZ 4 and 40/km^2 in AEZs 5 and 6. However, since 1930 there has been a relative shift of population to the more marginal areas, i.e. AEZs 5 and 6 (English et al. 1994), where populations have increased nearly ten times faster than in AEZs 2 and 3. The rapid population changes have necessitated complete changes in farming systems, i.e. intensification of crop production, major earth works to control soil erosion, clarification of land titles and, of great importance to this discussion, increasing problems of soil fertility decline and how to prevent it.

The District economy in Machakos has also changed substantially in response to better road communications and social factors. Cash crops have increased greatly in importance and seasonal trade between families in staple foodgrains, particularly maize, beans and

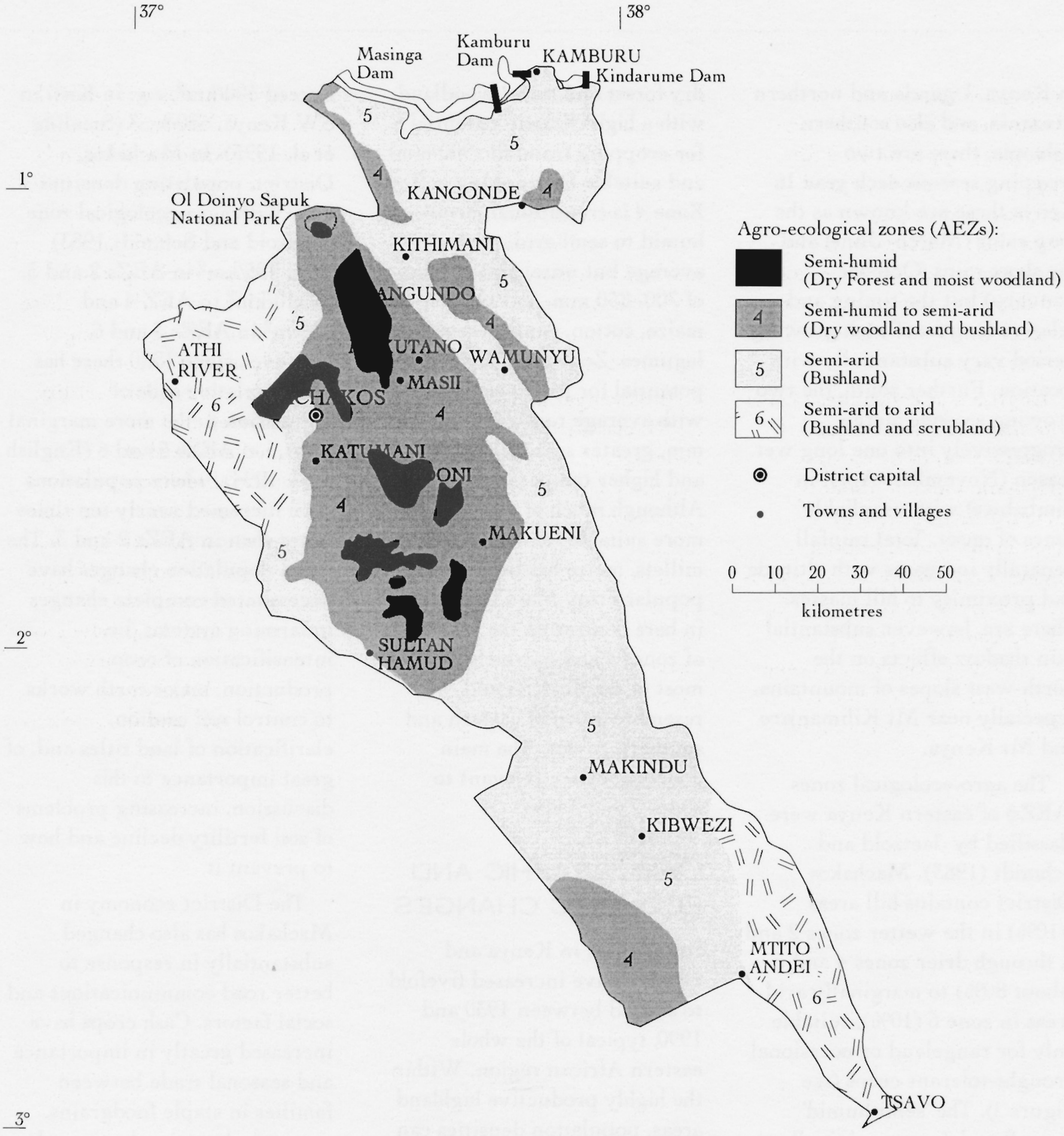

Figure 1. Kenya Agro-ecological zones, Machakos District.

cowpeas, is important (Rukandema 1984). There are now many opportunities for trade in farm products and purchase of farm inputs. Nevertheless, cashflow is always a problem in poorer households and demands such as school fees for children often take priority over farm inputs.

English and colleagues (1994) note that 'the effect of good market access in bringing information and stimulating agricultural change and investment is well known'. Unless there are easily accessible markets where produce can be sold to generate cash for the purchase of fertilizers and other inputs, there is no incentive to adopt high yield technologies. However, in Machakos this is not a major difficulty, since there has been a rapid rate of commercialisation in the District since 1930. There are now at least 700 regular markets and more than 8000 licensed shops and kiosks in rural communities (Tiffen et al. 1994).

Binswanger and Pingali (1988) classified countries on their 'agroclimatic population densities' (APDs), i.e. the number of people present per million kilocalories of potential food production, in contrast to the usual 'population/km^2' basis. On the APD basis, Kenya and Niger share the highest ranking in the world, both now and in projections to the year 2025. Among countries with mixed climates, Ethiopia, Kenya, Malawi, Rwanda and Uganda were grouped along with India and Nigeria as already having APDs exceeding 250 people per million kilocalories potential production. In producing these impressive data, Binswanger and Pingali did not consider present trends in soil fertility, and assumed that an intermediate level of agricultural technology would be achieved nationally in each case between now and the year 2025. Their findings highlight the importance of maintaining and improving the productivity of the land resource base in Kenya (cf. McCown and Keating 1992) and its neighours.

SPECIAL PROBLEMS OF THE MEDIUM POTENTIAL AREAS —

MACHAKOS AS AN EXAMPLE

THE COMPONENTS OF THE MIXED farming systems of Machakos, involving food crops, cash crops, tree crops and livestock, have been described by Lynam (1978), Rukandema (1984), Lee (1993) and Tiffen et al. (1994). Interacting demands for labour, nutrients, cash resources and management decisions are found at various levels. Most farmers use ox-drawn ploughs for major cultivation, but much weeding is done by hand with hoes, and other farm equipment is often minimal. Where all cultivation is with hand-tools, the cultivated area is usually restricted to about 1 ha/farm. The use of animal draught power allows about three ha of cultivated cropland whereupon the availability of labour for weeding becomes limiting, even though total farm area may be 5–10 ha (Rukandema 1984). Since a typical household may contain about 10 people, a single hectare of cropland would have to yield around one tonne of cereal grain equivalent twice a year simply to supply members of the family with 2000 calories/day. Considering the probabilities of seasonal and soil constraints and losses due to pests, it is not surprising that periodical food shortages occur, particularly as farm sizes gradually decrease. Here, only those aspects of the farming systems pertaining to soil fertility management are discussed.

There is strong interaction between livestock and cropping activities. Livestock provide manure and draught power, while cropping activities provide crop residues for livestock feed. However, there is significant conflict between livestock and soil fertility enhancing activities. For example, crop residues and maize stover which could be returned to the field to reduce run-off and provide nutrients for future crops are commonly used as feed. Food security remains an important objective for farmers in Machakos. Livestock have traditionally been a means of raising cash when needed.

Table 1 shows selected socioeconomic aspects of the farming systems in Machakos. In this study by Ockwell and colleagues (1987), the farmers were grouped according to their rates of adoption of various selected technologies. The technologies adopted by the different groups are shown in the second row of the table. Average farm sizes of the groups ranged 5–24 ha; individual farm sizes, 1.2–32 ha. The farms were all multi-enterprise crop and livestock production units. A trend of increasing prosperity can be traced from group 1 to group 4, e.g. in expenditure on school fees.

Table 1 indicates that, on average, at least one member of each household works off-farm. Tiffen and colleagues (1994) estimated that, for farmers in AEZ 4, 52% of their cash income was from non-farm work; for farmers in AEZs 2 and 3, about

39% cash income is from non-farm activities. Most able men have at least part-time off-farm work. This ranges from local work as labourers to employment outside the District, e.g. in Nairobi or in Coast Province as migratory workers.

THE SOIL SITUATION

Machakos District has soil resources and rainfall expectancies typical of much of eastern Africa. It is a well-studied area from an agricultural viewpoint because of its periods of overexploitation and consequent soil erosion of the cropped lands in the last 50–60 years (Tiffen et al. 1994). Machakos and its similar neighbouring District Kitui have undergone large increases in agricultural production, soil conservation and other aspects of development. However,

Table 1. *Household characteristics and patterns of technology adoption of different groups of farmers (mean values per farm).*

	Group 1	Group 2	Group 3	Group 4
No. of farms	5	5	4	2
Technologies adopted	Farmyard manure, terraces, improved fodder	Early planting, terraces, maize, farmyard manure, beans, improved fodder	Farmyard manure, terraces, ox-plough, chemicals in crop storage, improved fodder, early land preparation, early planting	Early land preparation, early planting, farmyard manure, terraces, ox-plough, chemicals in crop storage, improved fodder, chemical protection in the field
Farm size (ha)	5.0	15.9	6.2	23.8
Crop area (ha)	2.9	4.4	3.3	6.5
Grazing area (ha)	2.1	11.5	2.9	17.3
Crop to grazing area ratio	1.4	0.4	1.1	0.4
Livestock units per grazing ha	2.9	1.1	2.2	0.6
School fees per dependant (Kenya Shs)	124	340	1262	1758
Off-farm income[a]	0.4	1.0	1.5	1.5
Maleness[b]	0.4	1.0	0.4	0.7
Agedness[c]	0.6	0.2	0.0	0.0

a The figures in this row refer to the average number of individuals working off-farm.

b A farm with a male decision-maker is recorded as 1.0, with a husband and wife team, 0.5, and a female decision-maker, 0.0.

c A farm with a decision-maker 60 years of age or less is recorded as 0.0, more than 60, 1.0.

Source: Ockwell et al. (1987)

because of the strain on the soil resource imposed by intensive cropping with low nutrient inputs, many farmer households in Machakos are still threatened by encroaching poverty. Unless their economic position can be alleviated quickly, they are likely to descend further into poverty spiral from which escape becomes increasingly difficult (Fig. 2).

The main physical factors contributing to the decline in soil productivity, and hence to farm poverty, have been described by Okwach and colleagues (1992) and are shown in Figure 3. Largely in parallel with the operation of the poverty spiral, Figure 3 depicts a cycle of increasing soil degradation as organic and nutrient inputs diminish along with increasing household poverty and reduced crop yields. With reduced soil organic matter in the surface layers, infiltration rates for rainwater are lowered and the run-off of excess water increases, carrying with it the relatively nutrient-rich surface soil. Thus both valuable soil and potentially productive water are lost. Figure 3 also shows the priority of a poorer household to feed crop residues to livestock, and possibly to sell the vital nutrient-containing manure or to sell the residues directly, rather than returning them to the land. This contributes further to general soil depletion.

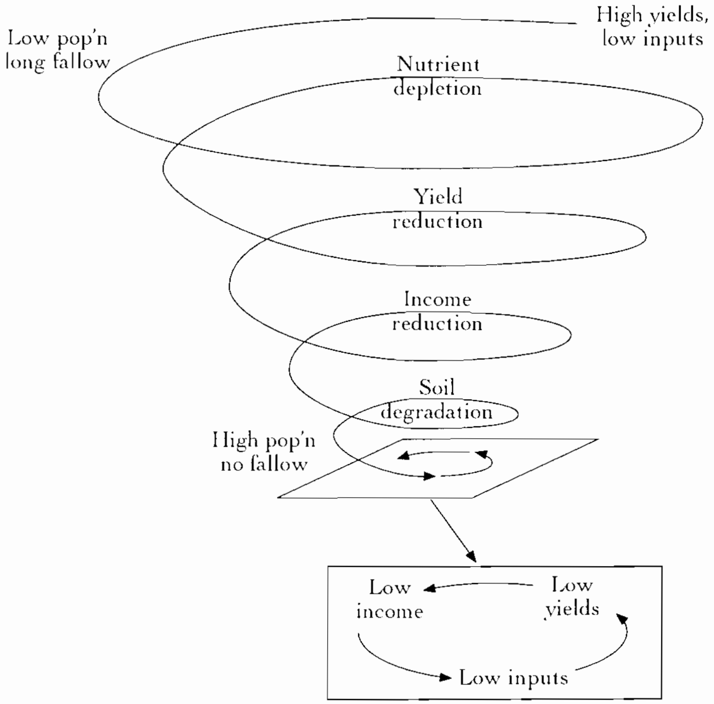

Figure 2. *The downward spiral to the poverty trap (McCown and Jones 1992)*

THE CLIMATIC RISKS

The erratic nature of rainfall patterns during the two wet (i.e. crop-growing) seasons has been described by Stewart and Hash (1982) and Tiffen and colleagues (1994). Coefficients of variation in seasonal rainfall commonly exceed 50% (Keating, Siambi and Wafula 1992). Because of this seasonal unreliability,

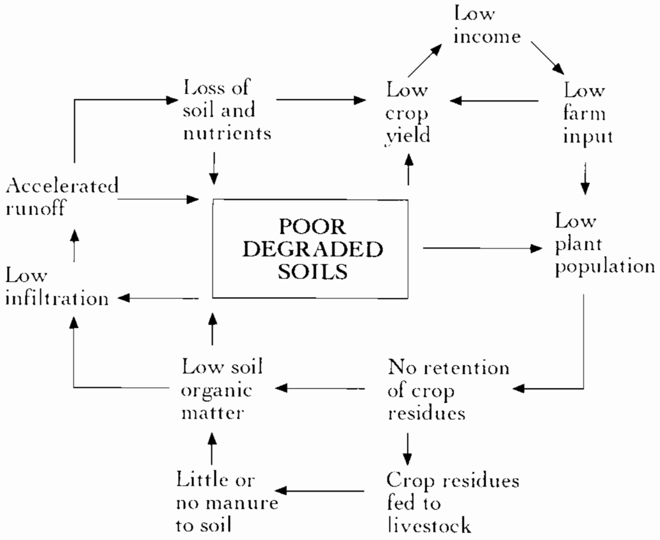

Figure 3. *The conflicts that lead to unsustainable land use for a typical subsistence farmer in semi-arid Kenya (Okwach et al. 1992).*

farmers are conservative and risk-averse in their attitude to possible yield-improving inputs (Rukandema 1984; Muhammad 1996). As in many other regions of the semi-arid tropics, rainfall occurs in events of unpredictable intensity. Delays in planting maize at the start of the wet season bring risks of significant losses in yield, proportionate to the time delay (Keating et al. 1992a). Similarly, moisture must be conserved as it is received, and populations of crop plants must be restricted to maximize the potential seasonal production.

IMPROVEMENTS IN AGRONOMIC PRACTICES

Many improvements by farmers in Machakos have been recorded in the last 30–50 years. These include the adoption of Katumani early maturing maize, ox-ploughing, early planting, use of insecticide to control infestations of maize stalk-borer, and increased manuring. One of the most impressive features of the agricultural landscape is the widespread terracing of the croplands, using hand-dug contour trenches and banks (known by the Kiswahili term as 'fanya juu' terraces). These very necessary structures were gradually developed to prevent the tragic and huge soil losses which occurred in the 1930s and in some subsequent periods of neglect (Tiffen et al. 1994).

RECENT RESEARCH ON INTERACTIONS AFFECTING MAIZE YIELDS

The extent of the seasonal variations, the varied degrees of depletion in the nutrient contents of soils on different farms or on different terraces within one farm, and the dependence of yield potential on management practices such as earliness of planting, planting density and moisture conservation, all interact as factors controlling final crop yields. These interactions have proved a serious obstacle both to farmers' willingness to risk investments in possible crop yield improvements and to agronomic research, since experimental results are often inconsistent from one site or season to the next.

Keating, Siambi and Wafula (1992) and Keating and colleagues (1992a,b; 1994) tackled this research problem, at least for maize agronomy, by developing and adapting a crop simulation model, derived from CERES-Maize (Jones and Kiniry 1986) and named CMKEN, which can predict the interacting effects of seasonal rainfall, soil conditions and management practice on maize growth, development and grain yield.

The CMKEN model has proved its ability to predict maize yields over a wide variety of field conditions with tolerably good precision (typically, $r = 0.95$). Using typical soil data and the detailed daily rainfall records for different locations throughout Machakos and Kitui, the model has enabled researchers to explore the likely outcomes of changes in farm practice such as plant population density, moisture conservation, and changes of maize variety. Of particular significance to the present discussion, the CMKEN model has been used to predict the likelihoods of profitable increases in crop yields when soil fertility has been improved. The most commonly deficient nutrient is N, which can be applied as organic manures or in soluble inorganic forms as fertilizer. The quality and availability of nutrients in boma manure are largely uncontrolled (Probert et al. 1992) — therefore the model has been used to investigate effects and climatic risks of using fertilizer N in eastern Kenya, rather than the use of manure (Keating et al. 1991; 1992a). The economics and risks of supplementary fertilizer N application were further explored at seven selected locations, representing a variety of rainfall regimes across Machakos and Kitui Districts, matched with two contrasting types of soil conditions, by Probert and colleagues (1994).

The conclusions of this research are discussed in greater detail below. In briefest summary, research has indicated and continues to confirm, that with a fairly high standard of management, which should be feasible for many farmers in Machakos, use of inorganic fertilizers to complement locally produced organic manures should be economically attractive with tolerably low levels of risk. However, a great deal of adaptive on-farm research and demonstration in collaboration with farmers remain to be completed. Many farmers still need to be convinced that affordable techniques to improve and maintain soil fertility can be developed within their own particular financial constraints and continual crop production demands.

MAINTAINING SOIL FERTILITY IN MACHAKOS — SOME POSSIBLE INTERVENTIONS FOR FARMERS

RATES OF SOIL FERTILITY DECLINE UNDER CONTINUOUS LOW-INPUT CROPPING

Research into the farming systems of Machakos during 1980–93 has examined socioeconomically feasible ways of restoring and maintaining soil fertility. Before considering these it is logical first to establish, as far as possible, just how much the soil has declined in fertility with farmers' current methods. Careful analysis has to be made of the available evidence.

It is beyond doubt that soil fertility is very low on many farmers' cropland fields. There is overwhelming evidence that soil fertility on the croplands of eastern Kenya (Machakos and Kitui Districts) is already seriously limiting crop yields in many seasons (Nadar and Faught 1984b; Okalebo et al. 1992; Probert and Okalebo 1992). Most soils in eastern Kenya are low in organic C, with low reserves of available N and P, even under natural vegetation. Denudation under grazing and sheet soil erosion over the past few decades are partly responsible for this in some locations (Tiffen et al. 1994). Further, there is evidence that nutrient deficiences emerge soon after the cultivation of previously rested land if supplementary nutrients are not applied (Okalebo et al. 1996).

First principles dictate that such nutrient deficiences must occur on the Alfisols of eastern Kenya with the current low nutrient inputs because each 1 t/ha crop of maize can be calculated to remove 20–40 kg N, 2–4 kg P and 15–30 kg K (using the data of Qureshi 1987). These figures agree with the negative nutrient balances derived for similar agro-ecological zones by Stoorvogel et al. (1993). Evidence from long-term cropping experiments in other parts of Africa, notably northern Nigeria and western Tanzania, corroborates that yields decline to very low levels in just a few seasons unless substantial amounts of nutrients are applied (Greenland 1994). The following examples provide additional evidence that a decline in fertility occurs quite rapidly in soils related to those in Machakos when they are continually cultivated and cropped with little or no nutrient inputs.

In north-eastern Tanzania, Haule and colleagues (1989) working on a soil sequence (catena) from chromic luvisols to ferralsols found a rapid loss of soil C in the cultivated layer and associated reductions in maize yields under annual cropping. Organic C decreased by 30–40% on all of three soil types from the first four-year period to the next four years. Exchangeable K decreased similarly by 17–40% on the same soils, accompanied by decreases in pH. During the same periods, unfertilised maize yields decreased by up to 45%, e.g. on the luvisol, from a 4.2 t/ha average to 2.6 t/ha in the next four years.

On a more fertile nitisol under continuous cropping at Kabete near Nairobi, Qureshi (1987) also found a decline in unfertilised maize yields of about 40% (3.3 t/ha to 1.9 t/ha) from one five-year period to the next. Yields in the second five years were improved to levels above those in the first period (from 4.6 t/ha to 5.2 t/ha) by applying combinations of organic manure and inorganic fertilizers. Manure or fertilizer applied singly produced rather smaller increases in yields but were still able to provide sustained high maize yields. Qureshi found that nutrients removed from the soil in grain and stover by the first maize crop amounted to N 91 kg, P 16 kg and K 139 kg/ha. Most K removal was in the stover, most P was in the grain, and the N removed was nearly equally divided.

Evidence from Machakos on soil changes over time is also accumulating. Mbuvi (as quoted by English et al. 1994) found marked reductions in soil organic C and N contents of the cultivated layer after long-term cultivation in the Kilungu area. Comparing sites under natural vegetation, under grazing and under cultivation and cropping, Mbuvi found a marked contrast from 2.49 to 1.25 to 0.74% C for the respective sites (Table 3). In the same soil samples, organic N, available P, and exchangeable K had all decreased in parallel with the changes in C. The changes in crop yield with time could not be established but major reductions are probable (Probert and Okalebo 1992). Mbuvi also sampled cultivated sites in the Makueni area of central Machakos in 1977 and again in 1990, in an attempt to determine the rates of soil changes with time under cropping. These data were indecisive, however, showing decreases in available P and K with time (47% and 20% respectively), but lesser changes in organic C and N. Interpretation is not clear, and could mean either sampling errors between the dates or some unknown stabilisation or inputs of organic matter.

Pronounced falls in organic C were also reported by Mwonga and Mochoge (1986) for a chromic luvisol near Katumani, Machakos, during 16 years of low-input cropping. Here, the cultivated soil contained about 33% less C to 50 cm depth than soil at an adjacent site under grassland. The changes in C, and parallel changes in N, occurred in each 10-cm depth layer from the surface. At 0–10 cm the change, comparing several sites in each category, from 1.85% to 1.23% C (and 0.172% to 0.120% N) was highly significant statistically.

It is probable that some of the organic matter and nutrient loss in some of these reports was due to enhanced physical soil erosion under cultivation. More detailed studies at the National Dryland Farming Research Centre, Katumani (Okalebo et al. 1996) were made in a well-documented experiment in which all soil erosion events were also monitored (Okwach 1994). The analyses revealed a gradual loss of organic C and N, amounting to about 20% of the total C and N in the 0–15 cm soil depth, during five years of maize cropping without nutrient inputs. These losses were several times greater than could be explained as physical erosion, according to analyses of the run-off soil after the worst erosive events. At this site, return of maize stover as a mulch each season, and applications of 70 kg N plus 10 kg P/per ha to each crop as inorganic fertilizer, prevented soil depletion and produced a doubling of average maize yields from 1.3 to 2.8 t/ha.

The continual application of inorganic N fertilizer, mainly as calcium ammonium nitrate, for five years (10 crops) was found by Okalebo et al. (1996) to have caused some acidification of the surface soil (a decrease from pH 6.14 to pH 5.78 at 0–15 cm depth). This observation is a reminder that the long-term use of such fertilizers, although not causing any detectable loss of soil productivity on this site so far, has to be managed with caution on the poorly buffered Alfisols of eastern Africa. Use of inorganic fertilizer in modest amounts strictly to supplement applications of organic nutrient sources, such as animal manure, where supplies of such sources are inadequate to satisfy crop nutrient demands, is one way of avoiding or reducing the problem (McCown and Jones 1992). This practice is discussed further in later sections (as 'fertilizer-assisted soil enrichment' or, more commonly, 'integrated nutrient management').

In summary, it is clear from the evidence presented and corroborated elsewhere that soil fertility in eastern Kenya, as in comparable soils in other parts of the world, declines fairly quickly under low-input cropping to levels of nutrient supply which restrict crop growth. When this happens, the return to a farm household for its labour inputs falls, even in good rainfall seasons. It is not possible to state accurately the annual rates of fertility decline for various soil types under different farming systems. The answer to this question would require tedious, expensive long-term research which has not been completed. Certainly there is overwhelming evidence that present management practices cannot sustain acceptable yields for typical farm households — which could avoid their descent into the poverty spiral.

The cause of fertility decline, apart from the obvious drain on P and soil cations by crop removal, is ultimately a negative balance in soil organic matter. The rates of depletion of organic C and N through microbial mineralisation and crop removal in the intensive cropping systems described often exceed their rates of replenishment from crop roots, residues, other farm organic inputs and biological N_2 fixation. Soil organic matter is an important repository for plant nutrients (N, S, P and exchangeable cations). It reduces acidification and improves both soil aeration and water infiltration. Maintenance of a moderate soil organic matter content thus becomes an essential part of sustainable land management.

The use of inorganic fertilizer N alone, on soils already depleted in organic N, enables substantial crop yields to be maintained only as long as the supply of other nutrients, particularly P, is adequate and problems of soil water loss due to surface capping can be avoided. A combination of organic inputs and supplementary applications of fertilizer N therefore looks a more attractive management option to researchers (McCown and Jones 1992). But what can a resource-poor farmer do, within socioeconomic constraints and using materials available around the farm, to maintain cropland productivity? Possible alternative inputs that can be considered include:

(a) the use of animal manure, and its extension by making composts;

(b) return of crop residues to the soil, instead of feeding them to animals;

(c) grain legumes in the rotation, or intercropping with maize;

(d) agroforestry by relay intercropping (e.g. Sesbania) and short improved fallows and the use of tree litter;

(e) renovation of the denuded grazing lands by pitting and legume plantings;

(f) inorganic fertilizers, in amounts tuned to climatic conditions — possibly involving response farming; and

(g) integrated nutrient management (combining organic and inorganic inputs).

Each of these inputs and technologies has characteristic benefits and costs to the farming system, summarised in Table 2. The following section discusses the variety of options and management decisions involved.

BOMA MANURE AND COMPOSTS

Application of manure which has collected in a small 'boma' or 'kraal' where livestock have been penned between their morning and evening escorted grazings for up to a year, is a popular means of maintaining soil productivity in eastern and southern Africa. In Machakos and Kitui Districts, 83% of farmers interviewed in 1990 (Muhammad and Parton 1992) reported using animal manure on their cropland. Similar high usage of the practice was reported for Chivi communal area in southern Zimbabwe, but here the supply of manure was sparse due to low cattle numbers after drought (Mombeshora and Mudhara 1994). Other Zimbabwean researchers (Sithole and Shoko 1991) also found high use of manure (63% and 83% respectively) in the communal areas of Shurugwi-Chiwundura and Wedza.

Despite this high popularity, manure use and effectiveness are limited by a number of factors, reviewed by Probert and colleagues (1992). Firstly, the supply of boma manure is not adequate to supply the nutrient demands of the crops grown in many medium potential areas. Diminishing livestock numbers relative to the growing human populations (English et al. 1994) and increasing demands for food crops will probably aggravate this situation. Also, methods of handling the manure lead to a major loss of nutrients and inefficient application. Kenyan and Zimbabwean studies (Probert et al. 1992; Mugwira and Shumba 1986) agreed that the manures applied to the cropland were low in N (e.g. mean of 0.42% N, in Kenya) but remained a valuable source of P (mean 0.17%) and K (0.88%). The manure samples had high contents of sand and ash

Table 2. *Characteristics of some appropriate technologies for maintaining soil fertility in eastern Kenya.*

Technology (input)	Advantages	Disadvantages	Long-term soil effects
Boma manure and composts	On-farm production — no cash outlay	High labour costs of extraction, processing, transport and spreading. Often not available in required amounts	Increases soil organic C and N, and availability of both moisture and other nutrients
Crop residues as mulch	On-farm production — no cash outlay. Improves rainwater infiltration, reduces water losses from run-off	Labour needed for harvesting and returning to land after ploughing. Deprives farm livestock of dry. Season fodder. May increase some pest problems	Increases soil organic C, reduces erosion and improves soil moisture availability
Green manures	On-farm production of biologically-fixed N and organic C	Occupies cropland which would otherwise be under food or cash crops	Residual effects on soil N are less than those of animal manure
Grain legumes in the cropping rotation	Biological N-fixation accompanied by high-protein grain. Residues can be returned to soil. The break in cereal cropping may reduce diseases	Do not satisfy the full N demands of the accompanying (intercropped) or subsequent cereal crop. Effects are modest	Residual effects are positive but small
Agroforestry	The trees supply a variety of products, including animal fodder, mulching materials, fuelwood and fruit. Effects on soil organic C and N are positive. May recycle P, K and other nutrients	Possible competition between trees and annual crops for critical soil moisture and nutrients	Still a potentially useful technique for some medium-potential areas, but only if new adaptations can be satisfactorily incorporated into farming systems
Inorganic fertilizers	Low labour costs in application. A source of rapidly available nutrients (especially N and P). Usually produce good crop yield responses. Reliable quality. Can be used (N) after basal appplications of organic inputs to satisfy crop nutrient demands as modified by seasonal rainfall events	High cash outlay for resource-poor farmers. Risks of crop failure in poor seasons	Will help to maintain fertility if used together with organic inputs (manure, composts, etc). Continual use of heavy applications may cause soil acidification. It is the only final resort to maintain nutrient supply and yields when organic nutrient sources have been exhausted

(80–90%) and were therefore largely soil. Nutrients easily available to plants included mineral N (47–135 mg/kg), high extractable P (185–946 mg/kg by the Bray 2 method) and large amounts of K.

Evidence indicates that animal excreta lying in the boma/kraal becomes badly weathered so that much of its valuable N, especially the soluble and rapidly mineralisable fractions, is lost. This occurs either by volatilisation to the atmosphere as ammonia or by nitrification to nitrate followed by a combination of leaching and denitrification to N_2 gas during periods of excessive wetness (Freney and Simpson 1983). When the manure is finally dug out from the boma, it is so mixed with the underlying soil that its removal means transporting much unnecessary weight of soil. Considering the simple tools many farmers employ, i.e. transport by ox-cart, wheelbarrow, sledge or even on the shoulder, application to the fields farthest from the boma in the limited time between crops is a major problem. The result is uneven application with easily detectable patches of high and low available P in the same cropland terrace, and lower available P at increasing distances from the boma (Okalebo et al. 1992; Probert et al. 1992).

There are feasible ways of improving the efficiency of manure collection and use. These include roofing the boma (Materechera et al. 1995), building it on a well-drained rise where the interior does not become boggy in the wet seasons, heaping the manure to one side away from the cattle, and better means of transport to the fields. Some of these ideas have been tried in eastern Kenya (Tiffen et al. 1994) but none seems to have been adopted widely.

More broadly, other techniques have had greater impact. In some areas of Malawi, the boma/kraal is moved periodically across the cropland so that the noted beneficial effects of the animal excreta on subsequent crops can be exploited. The system is known as 'khola' (Makken 1993b) and enables large plots to be systematically manured. Similar systems of moveable bomas have been noted in Tanzania (Sukumaland), parts of Senegal, Madagascar and Ethiopia (Ruthenberg 1980, p. 84). In Kenya such systems are uncommon, but have been observed in use on a few farms in central and western Kenya (E.M. Gichangi, pers. comm.).

A more attractive practice, which seems to be growing in popularity as the demand for manure continues to exceed the supply, is to extend the quantity of manure by composting it with whatever organic residues are available. These may be crop residues, weeds with attached soil or litter and loppings from surrounding trees. This technique is being promoted in Kenya by the Institute for Organic Farming (KIOF), the Tropical Soil Biology and Fertility Programme (TSBF) and other NGO and mwethya (self-help) groups. Just how much the composting effectively conserves nutrients in the manure does not appear to have been studied. Using materials of high C to N ratio can prolong the composting process. Much crop residue is likely to be valued more highly as livestock feed in the dry season than as composting material, so materials less palatable to livestock tend to be used.

A project promoted by KIOF at Makaveti in Machakos is using a ubiquitous shrub weed, *Lantana camara*, mixed with boma manure to produce compost. The project is reported to be having a useful impact on more than 50 farmers (Tiffen et al. 1994 p. 243). Similar or related composting methods are being promoted by other mwethya or NGO groups in Machakos District (Simon Wambua, pers. comm). In the Central Highlands of Kenya KIOF has many other successful mwethya groups which actively promote organic farming (Cheatle and Njoroge 1993). Farm households without livestock have the choice of returning crop residues, as compost or mulch, or selling the material to livestock-owners. TSBF network programs in eastern and southern Africa (TSBF 1994) attempt to promote the value and adoption of integrated nutrient management, including organic residues and composts.

RETURN OF CROP RESIDUES AS MULCH OR GREEN MANURE

The competitive uses within mixed farming systems for crop residues, i.e. as a source of animal feed during the later part of the dry season when feed is scarce, and as a soil additive to maintain organic matter and supply some nutrients, are already noted. At present the livestock usually win and obtain the feed, even if some is trampled uneaten in the boma to become composted with manure.

Research has shown that return of crop residues, particularly maize stover, as a mulch after maize planting is valuable in reducing rainwater run-off, thereby increasing water infiltration, producing greater available moisture for crop growth in the subsequent season, and reducing the probability of soil nutrient losses in the run-off (Okwach et al. 1992; Okalebo et al. 1996). These beneficial effects are in addition to the nutrients, especially K, added in the mulch and the positive effects on the physical structure and cation exchange capacity of the surface soil (Okwach 1994).

In a context of integrated nutrient management (Janssen 1993; TSBF 1994), the use of residue mulch together with modest applications of inorganic fertilizer has a compounding or interactive effect (McCown and Keating 1992). On the one hand, the mulch creates greater moisture availability enabling the subsequent crop to respond better to applied fertilizer N. The crop then produces more stover so that, unless the farmer buys more animals to consume the extra feed, or sells the excess to neighbours, there will not be a demand for all the stover as fodder and the surplus can again be used for subsequent mulching. Such a scenario allows greater hope for a gradual upgrading of the farming system toward higher production, greater efficiency of labour and better sustainability.

Green manuring, i.e. the practice of growing a leguminous crop solely or mainly for the purpose of obtaining biological N_2 fixation and ploughing under the crop to enrich the soil in organic N, has not been adopted to any important extent in East Africa because of pressure to produce food and cash crops every season on all available cropland. Nevertheless, researchers in some countries continue to experiment with this appealing idea, motivated by the recent increases in costs of inorganic N fertilizers. In Malawi, current investigations centre on undersowing maize with annual legumes which are grown on after the maize is harvested, then dug or ploughed into the soil (Materechera et al. 1995). Such a practice is unlikely to appeal to farmers in Machakos because crops frequently incur moisture stress during the later stages of growth — this would be aggravated by competition from an understorey of growing legume.

GRAIN LEGUMES IN THE CROPPING ROTATION

Legumes play a vital role in African cropping systems, often intercropped with maize but also as sole crops alternated with cereals. The legumes form a vital source of protein in human diets, as well as a break crop against root diseases, an alleviation of the process of soil N depletion and possibly a source of residual soil N of value to the subsequent maize crop (Nadar and Faught 1984a). On the N-depleted soils of the eastern African medium potential croplands, there is no doubt that grain legumes fix much of their N requirement from the atmosphere. However, much of the N contained in the crop at maturity is harvested in the seed and pods. Only some leaves, roots and nodules are usually left to improve soil fertility. Thus Simpson and colleagues (1992), working on an N-depleted farm site near Wamunyu, Machakos, found that legumes (cowpea, pigeon pea and lablab) grown for two seasons in rotation with maize left behind an additional 40 kg N/ha in the soil profile, nearly all as nitrate. This was sufficient to increase subsequent maize yield by 300–400 kg/ha, but still well below maize yields on adjacent plots supplied with fertilizer N. The result is typical of experience in other African and semi-arid tropical environments with a range of grain legume species.

It must be concluded that legumes in the cropping rotation are a very valuable inclusion but do not solve the problem of sustaining soil fertility. Moreover, legumes make a positive contribution only to the N problem. They do not grow well if available soil P is low (Okalebo et al. 1992; Probert and Okalebo 1992) and do not fix atmospheric N_2 efficiently in this situation (Probert et al. 1994, and many others).

Of special interest here is the value of pigeon pea, *Cajanus cajan*, in crop rotations. In eastern Kenya, and a number of other semi-arid tropical environments, pigeon pea is grown as a relay intercrop with maize or other cereals. This shrub legume species stays in the ground for up to 12 months, flourishing on residual moisture after the cereal crop has been harvested and providing green pods, dry mature pods, then finally fuel from its woody stalks. Because of its deep root system, enabling it to exploit subsurface soil layers for their available P, this species is observed to thrive on many nutrient-poor sites, and to produce a useful yield during drought seasons when the cereals have failed to establish. Pigeon pea is thus a valuable inclusion in cropping systems on most farms in Machakos District. Studies of hardy, woody crop legumes of this type have influenced agroforestry researchers toward the current thrust to use leguminous tree species such as *Sesbania sesban*. With relay intercropping, Sesbania can be used in a promising new technique of short-term ameliorative fallowing, for soil improvement with a minimum disruption to the cropping rotation (Sanchez 1995).

THE PLACE OF AGROFORESTRY IN THE MEDIUM POTENTIAL AREAS

In his recent review of the developing science of agroforestry, Sanchez (1995) critically surveyed the possible benefits and disadvantages of growing annual crops in some sort of geometric arrangement alongside trees. The previously acclaimed formula of 'alley cropping', whereby the crop is grown in alleys some five metres wide between hedgerows of leguminous trees, is heavily discounted in Sanchez's review, as the result of recent analytical research. Although the trees, which are periodically pruned or lopped, do provide organic matter, mulch and nutrients to the crop, competition between the perennials and the annual crop plants for moisture, nutrients and/or light prohibits this formalised alley-cropping becoming established as a robust technique for resource-poor farmers.

On the other hand, in steep areas, planting perennial grasses and fruit trees on contour banks (fanya juu terracing) is well established as a beneficial stabilising practice to protect the banks from erosion (Hudson 1993). Mixtures of crops and trees are grown widely across the varied agro-ecosystems of East Africa, apparently to farmers' advantage and satisfaction. Fruit trees such as pawpaws, mangoes, bananas and citrus are grown in strategic locations on many farms in eastern Kenya. The increased fertility surrounding leguminous trees of *Acacia tortilis* (Belsky et al. 1989) and *Acacia albida* (Sanchez 1995) is often noted. Even non-leguminous trees such as *Grevillea robusta* are prized on many farms as a source of fuelwood and building materials.

Current agroforestry research is pursuing and designing better systems for the juxtaposition of trees and annual crops in small-scale farming, to exploit the advantages that some tree species offer in capturing subsoil nutrients, especially P, leached nitrate and K, providing organic C and bringing all these into the reach of crop roots. To be successful, however, all this must be achieved without incurring the detrimental competition for moisture observed in alley-cropping. The leguminous multipurpose trees being studied, such as *Sesbania* spp., can provide valuable high-protein fodder for cattle to supplement the low quality dry feed which remains in the dry season, as well as improving soil nutrients (Dzowela and Kwesiga 1994). There appear to be two main research approaches to capturing the advantages of such a system on small farms.

The first is that described by Sanchez (1995) and referred to above, of interplanting the tree seedlings (or sowing the seed) between rows of a young crop, then allowing the trees to grow on with protection from grazing, after the crop has been harvested. This method would be appropriate for a site of exhausted cropland producing very little crop, allowing it to become a source of browse and fodder, or loppings and mulch for adjacent cropland, for one, two or more years (Dzowela and Kwesiga 1994), with the expectation of improved crop yields after the trees have been removed for fuelwood or sale. Such a method is showing good promise at a number of experimental sites in Zambia, but considerable adaptive research and extension are still required. The second possible technique also requires substantial research and adaptation, but could evolve out of research into the renovation of denuded grazing lands in eastern Kenya, as discussed below.

RENOVATION OF THE GRAZING LANDS USING PITTING AND AGROFORESTRY TECHNIQUES

A promising technique to involve agroforestry and multipurpose trees in the amelioration of exhausted croplands has been considered above. Sometimes in eastern Kenya, however, as in other parts of eastern Africa, the grazing land within farm boundaries and adjacent to the protected cropland terraces can also be seriously degraded. These areas are usually denuded at some times of the year due to excessive grazing by farm livestock. On sloping ground the continual denudation accentuates the run-off and loss of valuable water, and leads eventually to serious soil erosion. Researchers at the National Dryland Farming Research Centre, Katumani (Simiyu et al. 1992) developed a pitting technique to capture the potentially lost run-off water in a contiguous series of micro-catchments or pits, each about 2 m^2 in area, constructed down the slope. The area was revegetated by sowing cowpeas as a cash crop to recoup the labour costs, and a mixture of fodder legumes to provide a canopy, to fix atmospheric N_2 and provide grazing. The technique aroused the interest of several farmers, but clearly requires further study because of the labour costs involved and the need to fit the construction of the pits into the long dry season (July–September in Machakos) when labour is available. The Katumani group noted the possibility of growing trees within the pits, but did not initiate studies along these lines.

Leguminous tree species such as Sesbania planted in the Katumani pits could provide a means of ameliorating the site for future cropping as the needs of the farm family expand. Alternatively, the tree prunings could be spread on the neighbouring cropland as a source of nutrients and organic C. The established trees would remain a valuable source of fodder for farm livestock. The economics of such techniques, in terms of milk and meat production, have been assessed very positively (Lubulwa et al. 1995).

THE STRATEGIC USE OF INORGANIC FERTILIZERS TO SUPPLEMENT ORGANIC INPUTS

From the work of Stoorvogel and colleagues (1993), Smaling (1993) and others, the croplands of much of sub-Saharan Africa are being drained of their plant-available nutrients during intensive cropping, with only minor inputs of nutrients from outside. The main economically feasible ways in which the nutrient drain can be slowed using methods and inputs generated on the farm, with household or hired labour, are reviewed above. These organic inputs are extremely valuable in the medium potential areas. However, the materials are bulky to transport and often, as is the case for animal manure, just not available in the quantities required. Farm equipment and labour supply are often inadequate for the tasks of loading, pruning, transporting and evenly spreading and burying the materials (especially when the most able-bodied men are absent from the farm). Moreover, knowledge and skill are required to obtain a release of nutrients from organic sources at the times most needed by the crop (Myers et al. 1994).

To overcome these problems, a resourceful farmer may choose to supplement local supplies of nutrients by purchasing and applying modest amounts of inorganic fertilizers. The agronomic and economic potential of this technology seems attractive for substantial areas of nutrient-poor cropland in AEZs 4 and 5 of eastern Kenya (Keating et al. 1991; McCown and Keating 1992; Probert et al. 1994). Several authors have acknowledged that the most robust and socioeconomically attractive technology is to complement locally grown resources with purchased inorganic fertilizer, rather than aggressively attempt to replace organic supplies with inorganic sources. McCown and Keating (1992) use the term 'fertilizer-augmented soil enrichment' (FASE) to describe the combined resources approach. Others (Janssen 1993; Swift et al. 1994; Okalebo and Woomer 1995) adopted the term 'integrated nutrient management' (INM).

Machakos District farmers who have adopted FASE or INM find that it provides flexibility in seasons of uncertain rainfall because a minimal basal application of inorganic N and P (as diammonium phosphate) can be applied at maize planting, after the organic inputs. Then, after the initial nutrients have been utilised, the young crop depends on mineralisation of N from the organic sources until seasonal prospects become clearer. Continuing good rainfall on the growing crop becomes the signal for a late side-dressing of soluble, quick-acting N fertilizer (e.g. calcium ammonium nitrate some 30 days after planting). A conditional use of supplementary N fertilizer in this way offers some advantages in economic risk management (Wafula et al. 1992).

The potential for integrated nutrient management in sub-Saharan Africa has been critically reviewed by van Reuler and Prins (1993). These authors, while conceding that a substantial lift in food production can come only from applications of externally derived nutrients to cropland, still place high value on INM. They advocate optimising the use of all possible local sources of nutrients before importing inorganic fertilizer, pointing out that the successful introduction of fertilizers requires a good infrastructure of traders and transport, plus a major effort in farmer education.

Results of a survey by Gerner and Harris (1993) of 14 countries indicate that most of the fertilizer consumed in sub-Saharan Africa is applied to cash crops, e.g. cotton (17%), wheat (14%), sugarcane (11%) and tobacco (5%), but some 24% of the total was applied to maize and 8% to sorghum. Whereas nearly all the sugarcane and tobacco received fertilizer and 63% of the planted cotton area, only 16–17% of the maize and sorghum areas received inorganic fertilizer. These data could be somewhat biased toward larger-scale producers with greater financial resources, as they account for less than half the total consumption of fertilizer.

Government moves to cut subsidies and privatise the distribution systems in many countries have led to sudden price rises and local scarcity of supplies. The great value of inorganic N fertilizer is that it can produce a rapid response in the crop, if it is applied when moisture and other seasonal conditions are favourable. Thus to have supplies of the appropriate forms of nutrients, in affordable packages when and where farmers need them, is essential for the successful adoption of this technology. In Kenya, a very positive move has been made recently — small packets of fertilizer, 2–10 kg, are now available in some locations.

Among possible P sources, a material cheaper than superphosphate now available in Kenya is the ground rock phosphate from a natural deposit at Minjingu in northern Tanzania. This high grade material (30% P) had good residual availability to crops when tested on a P-deficient soil near Katumani, Machakos (Probert and Okalebo 1992). In partially (50%) acidulated form it produced yield responses in maize almost equal to the effects of equal amounts of P applied as single superphosphate (the more expensive 100% acidulated form).

ECONOMIC ASPECTS OF MAINTAINING SOIL FERTILITY

AN IMPORTANT ASPECT OF THE economics of maintaining soil fertility is the sustainability of farm productivity through the nutrient-supplying capacity of soils. Tandon (1995) recently defined sustainable agriculture:

> *A sustainable production system should not just draw from the resources, it should have a pre-planned provision to plough back part of the profits into conservation and improvement of the resource base to enhance its quality and production capability. Sustainable farming thus goes beyond raising crops and animals.*

In places like Machakos District, sustainable farming is made even more difficult because not only are land and water resources under pressure, the financial resources of farmers are seriously limited. Thus there is great temptation for farming to degenerate into the environmentally destructive and ultimately self-destructive activity of survival farming (McCown and Cox 1994). A similar point is made by Sanders and colleagues (1995) who comment that:

> *In much of sub-Saharan agriculture, the breakdown of the fallow system due to population pressure and the disappearance of the frontier have not been accompanied by increased input purchases to raise soil fertility. Instead, the result has been soil degradation through mining the soil for the available nutrients or by pushing crop production into more marginal regions previously used for grazing.*

Unanimity is not a common feature when it comes to how to go about encouraging sustainable agriculture for resource-poor farmers. At one extreme, some researchers believe that governments can provide the solution to the problem. For example, McCown and Cox (1994) argue that:

> *where circumstances force economically-rational farmers to farm in ways that are unsustainable and damaging to present and future society, there is a need for innovative policy initiatives. Soil erosion is a problem in political economy.*

On the other hand, Tiffen and co-workers (1994) strongly argue that the steady improvement in knowledge and in the resource base of farmers in Machakos cannot simply be ascribed to government action, rather it is the result of individual and village level investments and initiatives.

The truth probably lies somewhere in the middle, where a combination of good government policy and appropriate farmer attitudes to land management together contribute to eventual improvement in the quality of the resource base.

A more difficult exercise is determining whether resource enhancement has occurred or not. For the economic analysis of natural resources, Pearce et al. (1988) suggested a framework with the following components:

- assess the quantity (erosion) and quality of soils over time;
- examine the factors determining the supply and demand for new land (population pressure) and possible imbalances;
- assess costs to the economy due to resource degradation;
- design incentive packages to improve resource management.

Ehui and Spencer (1993) suggest a measure of sustainability based on the 'intertemporal total factor productivity' (ITFP) and a growth accounting framework. ITFP is defined in terms of the productive capacity of the system over time. For a sustainable system, this productive capacity includes the unpriced contributions from natural resources and their unpriced production flows. ITFP is an appropriate measure of sustainability as it addresses the question of intertemporal change in the productivity of a system between two or more periods. A system is sustainable if the associated ITFP index, which incorporates and values changes in the resource stock and flow, does not decrease (Ehui and Spencer 1993).

Ehui and Spencer (1993) also suggest a measure of economic viability, a static concept which refers to the efficiency with which resources are employed in the production process at a given time. A new production system can be said to be more economically efficient than an existing one if its total factor productivity is greater at a given point in time. A key component in constructing either the ITFP (sustainability) index or the economic viability total factor productivity index is the inclusion of all inputs and all costs including the unpriced contribution from or impacts on natural resources. Analyses that exclude these unpriced factors are flawed.

Tiffen and colleagues (1994, chapter 6) state:

> *Agricultural output per person is an important measure of welfare in any economy where agriculture is the main occupation and where locally grown food is the main basis of family nutrition. Output per hectare is an important indicator of productivity, and also of sustainability, since falling output might indicate a deterioration in the resource base. District production is examined on a per head and per hectare basis, as measures of welfare and productivity which take into account the growth of the population and the increase in District area. This chapter therefore provides our main evidence for an increase in agricultural productivity which has substantially outpaced population growth.*

In this analysis Tiffen et al. (1994) made two main errors which throw doubt on their conclusions about increased intertemporal total factor productivity in Machakos.

(a) Inconsistency in the choice of reference periods

Tiffen et al. (1994, p. 94) state that to compare the value of output per head and per hectare over time, they converted all production to its 1957 value in maize. This means that for each year in their analysis, they undertake the following analysis:

$$Q_1 = \frac{Q_{1957,1}P_{t,1} + Q_{1957,2}P_{t,2} + Q_{1957,3}P_{t,3} + Q_{1957,4}P_{t,4} + \dots + Q_{1957,n}P_{t,n}}{P_{1957,Maize}Q_{t,Maize}} \tag{1}$$

In the above equation;

P is the price of commodity j where j = 1, 2, 3, … n;

$Q_{t,j}$ is the quantity at time t of commodity j;

t takes values for these years: 1930, 1957, 1961, 1977 and 1987

$P_{1957,j}$ /$P_{1957,maize}$ gives the terms of trade between maize and commodity j.

In the analysis, Tiffen et al. (1994) seem to carry out the above analysis for 1930, 1957 and 1961. The index in equation 1 is a modification of a well-known Laspeyres quantity index (Hirshleifer 1980). It expresses all other outputs in terms of 1957 maize values and would provide an estimate as to whether quantities have increased 'on the average' between two time periods. However, Tiffen et al. (1994) switch from equation 1 when it comes to analysing output for 1977 and 1987. They resort to current prices of maize and other commodities for both 1977 and 1987, making it impossible to compare the changes in value of output between 1961 and 1987. More importantly, the big increase in output between 1961 and 1977 could be due to nothing more than inflation in the prices.

(b) Inadequate emphasis on the unpriced factors

A more important omission in their analysis was inadequate emphasis on soil fertility in their construction of intertemporal sustainability indices. They report (1994, Chapter 8) results of their analyses of soil samples from the following three categories of sites in Kilungu, Machakos:

Group 1: were sites which had not been cultivated for over 60 years and are under natural vegetation;

Group 2: were sites which had been fallow for 20 years or more and are currently used as grazing land;

Group 3: were sites which had been under annual cultivation for 40–60 years or more without any known additions of fertilizers and little manuring.

The results are summarized in Table 3.

Tiffen et al. (1994) conclude that there is a definite trend of fertility decline at every site from Group 1 to Group 3 sites. Yet in their Chapter 6, where they construct sustainability indices for Machakos, no attempt is made to correct for this obvious soil mining impact. These data and other evidence presented earlier on the impact of cultivation and cropping on the fertility of soils in Machakos are grounds for serious concerns about sustainability of crop production there. Until an analysis is completed which takes into account and explicitly incorporates estimates of the cost of soil mining from the value of output in Machakos District, the overoptimistic picture painted in Chapter 6 of Tiffen et al. (1994) has to be interpreted with caution.

Table 3. Soil fertility changes at Kilungu, Machakos.

Property	Group 1 means	Group 2 means	Group 3 means
Soil pH (water)	5.50	5.40	5.00
Potassium (me%)	0.56	0.40	0.29
Calcium (me%)	8.70	2.40	1.10
Magnesium (me%)	3.40	1.40	0.90
Phosphorus (ppm)	23.00	14.00	13.00
Nitrogen (%)	0.35	0.18	0.11
Carbon (%)	2.49	1.25	0.74

me%: millequivalents exchangeable cation per 100g soil; ppm: mg extractable P per kg soil.
Source: Tiffen et al. (1994).

The problem of unpriced impacts associated with soil mining is especially important in the context of Machakos because the period covered by Tiffen et al. (1994) witnessed the introduction of higher yielding cultivars of maize, sorghum and other crops. Their introduction in a context where farmers do not traditionally invest in soil fertility enhancing technologies can increase the extent of soil mining (Bennison and Evans 1968).

Sanders et al. (1995) argue that if soil mining can lead to irreversible damage to soils, then soils must be considered as an exhaustible resource. The possibility of irreversibility means that a higher cost should be charged against soil degradation than just the estimated relation between yield decline and soil degradation.

FARMER RESPONSES TO NEW SOIL MANAGEMENT TECHNOLOGY

SOIL FERTILITY RESEARCH WILL have an impact on soil fertility and productivity in East Africa only when farmers adopt the results of the research. Without adoption, the financial and other resources invested in soil fertility-enhancing research have a negative return. Table 4 summarises literature on the adoption rates for fertilizers in selected areas of three countries. High levels of adoption of inorganic fertilizers have been reported in parts of Malawi with favourable environments for growing hybrid maize. Malawian growers of local maize varieties use fertilizers more modestly. In Machakos, the levels of adoption observed are much lower, as might be expected considering the unpredictability of rainfall and higher levels of risk. The final example, from a semi-arid zone of Zimbabwe, shows almost zero adoption of fertilizers on sorghum.

Interest in the use of inorganic fertilizers is gradually increasing in Machakos and the neighbouring districts of Kitui and Embu. However, Muhammad (1996) studied a sample of 94 farm households in eastern Kenya and found that between 1980 and 1990 the rate of increase in adoption of inorganic fertilizers was only 1.6% per year. Rukandema et al. (1981) and Muhammad and Parton (1992) estimated the rates of adoption levels for various technologies in eastern Kenya (Table 5). Compared with other technologies such as timely planting and use of improved seed, the use of inorganic fertilizers has progressed least along the adoption path.

Innovations requiring smaller direct cash outlays (organic fertilizers, terracing and early planting) are the most widely adopted. These comprise the poor person's technology (Muhammad and Parton 1992). Terracing and boma manure are complementary techniques for improving soil and water management, which place high demands on available labour but do not necessarily require cash for their implementation. Mulching is not used because the most readily available materials, maize stover or other crop residues, are valuable dry season feed for livestock.

EXAMPLES OF FARMERS' EXPERIENCE

In his survey of the use of inorganic fertilizers, Muhammad (1996) found that some farmers are at least interested in trying new methods of soil fertility improvement. The survey does not show, however, how much fertilizer those farmers continue to use after their first experiments. The following accounts summarise briefly the experiences of four households and a mwethya group over a number of years of familiarisation with fertilizer technology. Three of the farmers

Table 4. *A comparison of rates of adoption of inorganic fertilizers for three African countries.*

Country & Crop	Rate of adoption of inorganic fertilizers (%)	Source
Malawi		
Growers of local maize varieties	50	Smale et al. 1992
Growers of hybrid maize	87	Smale et al. 1992
Kenya (Machakos)		
Maize	18	Muhammad & Parton 1992
Maize	16	Muhammad 1996
Zimbabwe		
Sorghum	Low — close to zero	Chiduza et al. 1992

Table 5. *The rates of adoption of soil fertility-enhancing technologies and terracing in Machakos and Kitui Districts in 1980 and 1990.*

Technology	Adopters as proportion of all farms	
Date	1980[a]	1990[b]
Use of boma manure (organic fertilizers)	0.68	0.83
Use of N-fixing grain legumes	not estimated	0.22c
Use of inorganic N-fertilizers	0.08	0.18
Mulching	0.00	0.00
Terracing	not estimated	0.78[c]

a: Rukandema et al. (1981)
b: Muhammad and Parton (1992)
c: Ockwell et al. (1991)
Source: compiled by Lubulwa et al. (1995)

would have to be classified as 'above average' in their willingness to invest in new management methods. Family 'C' and the members of the mwethya group would, by contrast, be subject to all the socioeconomic constraints illustrated in Figures 2 and 3. A summary of family characteristics and experiences is given in Table 6. Farm sizes all lie in the 5–10 ha range. The soils in cases A and C would probably be similar if they had been managed in the same way (sandy loam alisols); those in cases B and D have textural similarities (sandy clay loams). The farm in case D has a steeper topography, making control of water loss by run-off more important, but this is compensated by a slightly higher average rainfall than the other cases.

Family A. This is an example of successful soil fertility management near Makutano (AEZ 4) in Machakos District. It began in 1970 after one of the wives of the family attended a one-week course on the use of fertilizer. She experimented first in a very limited way, was successful in growing better

Table 6. *Some examples of farmer's experience in soil fertility management.*

	Family A	Family B	Family C	Family D	Kivoto Mwethya Group
Technologies used on the farm (in addition to terracing)	Boma manure application, fertilizers, composting. A dam was constructed to trap run-off and provide limited dry-season irrigation for cash crops.	Boma manure application, some crop residues recycled, occasional use of fertilizers, tree planting on the margins.	A limited supply of manure is used.	Application of (N and NP) fertilizers, together with limited boma manure, composts of leaf litter, crop residues and ash.	Correct fertilizer technology. Combined use of composting, manure and inorganic fertilizers. Minimising water loss through run-off. Improving contour banks, pitting and revegetation of denuded grazing lands.
Experience with soil fertility management	Highly successful	Moderate success	Very poor adopter of soil fertility management technology	Highly successful	Highly successful
Attitude to new technology	Enthusiastic about experimentation.	Investments undertaken cautiously, or occasionally.	Large family (15 dependent children) has insufficient financial resources to adopt new technology.	Enthusiastic about experimentation. The family head earns a modest cash income, some of which is used to purchase the inputs.	Growing enthusiasm about experimentation. This is a cooperative of 120 women farmers, started in 1990. Some, because they used fertilizers inappropriately, had been disappointed about the value of fertilizer. The group is now eager to learn better practices.
Location	Near Makutano (AEZ4) Machakos	Mutonguni, Kitui District	Near Wamunyu, Machakos	Kakuyuni, near Kangundo, Machakos	Kangundo, Machakos District
Soil type	Sandy loam, low in organic matter.	Sandy clay loam, low in organic matter, but with good P status.	Sandy loam with low soil organic carbon (0.4%); N, P, and K all acutely deficient.	The farm is on a steep site (16–20% slope), badly eroded through previous denudation and abuse. Sandy clay loam, low in organic matter.	Badly eroded soils, with low and declining soil fertility. Much water lost through run-off.

Continued over page

Table 6. continued

	Family A	Family B	Family C	Family D	Kivoto Mwethya Group
Source of information about the technology	A government instruction course on the correct use of fertilizers.	Not stated, but has had contact with researchers and extension.	Has had contact with researchers for several years.	Head of the family was a driver/assistant to agricultural researchers, and so became interested in the problems of soil fertility management.	The driver/assistant to a research group (see family D) helped start this cooperative, working with the local community. He now helps to coordinate its activies, teaching from his own experience.
Crops and livestock produced	Maize, legumes, some citrus and dry season cash crops, e.g. tomatoes and brassicas	Maize, legumes, some cash crops. 10–12 cattle, a few goats	Maize with very low yields., (mainly pigeon pea), citrus trees (using the limited supply of manure)	Maize, legumes and other domestic food crops, a few small cattle	Maize, other food crops, and cattle

maize, and then was joined by her mother-in-law in producing crops such as tomatoes for sale. This cashflow enabled the family to make further purchases of fertilizer, and a small shop was set up to sell produce in the local village. The enterprise grew within the family to the stage when a dam could be constructed below the homestead, trapping runoff and facilitating irrigation of plots of brassicas and dry season tomatoes.

Now, fertilizer use, together with manure application, composting and a generally high standard of farming, is an integral part of whole-farm management. All this was achieved without any outside financing. The soil is fairly typical of the surrounding valleys — a sandy loam quite low in organic matter. From the beginning, however, the family was willing to invest in education and was enthusiastic about experimentation. In this respect, it seems to differ from its neighbours who have done little to copy its methods even though the farm is obviously well managed and prosperous.

Family B. This example shows moderately good management in Mutonguni, Kitui District. The family head is retired from the army and therefore has some pension. This allows occasional purchases of fertilizer or manure but, as money is scarce, these purchases are made only for specific reasons. The farm layout is contoured around the hill with the homestead and the cattle boma on the hilltop, surrounded by terraced cropland. This facilitates the transport and even distribution of manure from the boma to various terraces. The boma is in a well-drained position so that manure can be removed or stored more efficiently and with less nutrient loss than would be the case in a wet or muddy location (Probert et al. 1992). The 10 to 12 cattle and few goats graze in a neighbouring valley and so bring nutrients to the cropland. Phosphorus status of the soil is moderately good (22 ppm by the Olsen method), which enables legumes to be grown successfully around the terraces. Some crop residues are incorporated in the soil and tree plantings are made progressively around the margins. It seems that the family has been able through hard work and good thrifty management with just occasional outside purchases, to be self-sufficient in staple foods, plus making some cash sales of legume grain. It is probably too early to judge that the soil is in a sustainable equilibrium, but at least its fertility decline is being controlled compared with many other farms. The family was able to purchase additional land on a neighbouring degraded site and to terrace it with hired labour in 1990. It then obtained sufficient manure to improve the diminished nutrient status of this new site. This is a main project for the eldest son of the family, who eventually will be able to establish his own household there.

Family C. This family has an impoverished farm where the land is almost exhausted from continual cropping and very low nutrient inputs. The soil is a sandy loam alisol near Wamunyu, Machakos. Soil organic carbon is very low (0.4%). Nitrogen and P are both acutely deficient; available K is also low. Probably the soil nutrient resources have always been low, but have diminished further during a long period of cropping. Experiments on the site have shown marked responses to N and P fertilizers. Maize yields increased from 600 to 4000 kg/ha with applications of N and P, and cowpea yields increased from 1000 to 2000 kg/ha, with P.

Maize yields on the farm are generally very low and soil fertility urgently needs improvement. Legumes grow somewhat better than cereals, depending on the P status in their exact location, since P availability varies greatly both within one terrace and among terraces. Good maize yields were observed near the boma site where effluent occasionally runs onto the cropland after heavy rainfall, and close to trees of *Acacia tortilis*, where leaf and pod litter accumulate (compare Belsky et al. 1989). There is also an old disused boma site, where residual fertility has persisted, that still produces good maize.

The family group is quite large with about 15 dependent children and all the men except one, who is not physically robust, away working or looking for work off-farm. Since there are only four or five small cattle, the manure supply is meagre. Off-farm income and cash flow are insufficient to purchase external inputs. The only crop that does reasonably well is pigeon pea because of its extended root system, allowing plants to exploit the limited supplies of soil P, and its N-fixing ability. The limited supply of manure is currently used to establish citrus trees. Both equipment and draught power of the cattle are minimal. This family is struggling to find a way out of the poverty spiral. If appropriate techniques can be found, agroforestry on parts of the farm could help restore fertility, but an input of externally derived nutrients (at least P and K) also seems essential for sustainability.

Family D. This farm is in Kakuyuni Location near Kangundo, Machakos. In contrast to Family C, this small family of only two adults and one teenage child demonstrates what can be achieved to build up farm productivity in an erratic rainfall and depleted soil environment similar to those already described, with a modest cash income from off-farm employment and some educational experience for the household head.

The most critical factor is probably that the household head has been able, as part of his work as a driver and assistant, to travel around Kenya, particularly Machakos and Kitui Districts, and talk with agricultural researchers about the problems of declining soil fertility and low crop yields and their possible solutions. While working on a number of on-farm experiments, he was able to observe and appreciate the effects of better management, including the application of fertilizers. With this knowledge of possible techniques, suitably modified in scope to fit the household budget, the farmer experimented with N and NP fertilizers, appreciated their compatibility with his other limited nutrient input resources of manure from a few cattle, composts, ash and leaf litter. He therefore developed a system of INM (or FASE) to improve the fertility of his land. The rather steep farm site (16–20% slopes) had become badly eroded through previous denudation and abuse, so that terracing to prevent further erosion was a priority. Nutrient inputs were then used to improve fertility on the reclaimed terraces. The investments have been successful through the combined efforts of the family, with some hired help. The family say now that they never have to buy food, and that purchases of fertilizer have been far more profitable than being dependent on outside grain purchases. The crops treated with combined organic and inorganic nutrients look healthy, and the system now seems sustainable. However, it must be acknowledged that off-farm income has been a critical factor in building up the investment.

The family has deep roots in the local community, and knowledge of its success has permeated to the extended family and neighbours. The family has held field days, discussions and demonstrations with its neighbours, and this has helped the formation of a local Kivoto mwethya (self-help) group whose activities are described below. Through the mwethya group, the local Salvation Army church, the schools and the local political committees, this rural community has been able to broadcast messages on sustainable land management, and so become a valuable education force.

Kivoto mwethya group. This is a cooperative self-help group of some 120 farmers near Kangundo, Machakos District, organised by the local community and started in 1990. The farmers are mainly women because the younger men look for work elsewhere to maintain a cashflow, leaving the women in charge of day-to-day management. The origins of the group lie in the general poverty of the area; soils have been badly eroded and soil fertility has deteriorated. Seasonal rainfall is uncertain and spasmodic run-off has been a major loss of potential soil moisture. There are recurrent food shortages and hardships.

The primary aim of the group is as enunciated by the group leaders, 'the promotion of practical and positive attitudes to development in the community'. More specific agricultural aims are to protect the soil from erosion and increase the uptake of nutrients by crops. This involves minimising water loss through run-off, thus also preventing soil loss, and finding economically feasible ways of improving the soil nutrient supply by experimenting with combinations of compost, manure and inorganic fertilizer.

Longer-term aims include growing more animal fodder by grass plantings on the contour banks and wherever else is possible consistent with the soil conservation objectives. By obtaining better- grade cattle, the group aims to promote milk production both for home consumption and cash sale.

Recent activities have concentrated on soil conservation and revegetation of denuded grazing land, but better crop management and promoting correct fertilizer use are also priorities. Because fertilizer is now expensive, and better handtools were badly needed by the group, fundraising has been a priority. Despite this the group's achievements are impressive.

The group leaders have found that it takes much patient discussion to convince farmers to make any changes in their practices (cf. Liniger 1993). Farmers in the Kivoto mwethya group have shown suspicion of and declared disappointment about the value of fertilizers. They reported damage to young plants by fertilizer, and poor results. Questioning revealed widespread ignorance and poor techniques of fertilizer application, such as bad timing and use of the wrong chemical forms of fertilizer, e.g. calcium ammonium nitrate for basal applications close to the seed, and diammonium phosphate for late surface applications. Nevertheless, with education and demonstration the farmers have gradually responded more enthusiastically. The group leaders are continually instructing groups in better agronomic practices, from planting and fertilizer use to correct use of insecticides.

When the group obtained financial assistance from an NGO, its first priority was to purchase new tools and wheelbarrows to transport manure from the bomas to the terraced croplands. The farmers are developing a balanced approach using organic inputs (manure and compost) together with supplementary inorganic fertilizers. They are starting to re-evaluate their limited supplies of manure, using mixed composts and mulches of crop residues or tree loppings as the means of extending the effectiveness of their organic inputs, and minimising cash outlay on comparatively expensive fertilizer.

Greater food security has been achieved for the whole community. The work of this mwethya group is having a beneficial effect on the community of its sub-Location, and word is spreading to surrounding sub-Locations. The

Location Chief (Government appointee) is interested in the work of the group and publicising it as a good example of what can be achieved . The District Commissioner is aware of the project and is reported to be favourably impressed.

Clearly the success of the group depends on the continuing enthusiasm, knowledge and leadership of a few individuals on its organising committee. The committee reports that government extension services were having no impact on the farmers before the mwethya group's activities became organised.

WHY IS PROMISING NEW TECHNOLOGY ADOPTED SO SLOWLY?

Muhammad (1996) investigated possible factors that could explain differing levels of adoption of soil fertility-enhancing technologies. A summary of the factors investigated and conclusions as to their significance are compiled in Table 7.

Table 7. *Factors that might explain the differing levels of adoption of soil fertility-enhancing technologies.*

	Factor	Findings of Muhammad (1996)	Method
1	Lack of information about the technology	?	a
2	The cost of acquiring information about the technology	?	a
3	The cost of introducing and using the technology compared to benefits from existing enterprises	?	a
4	Attitude to risk	**	b
5	Farm size (average size 7.2 ha) and resource endowment of farming household	ns	c
6	Household demographic characteristics:		c
6a	— Household size	ns	c
6b	— Age	ns	c
6c	— Gender	***	c
6d	— Level of formal education	ns	c
6e	— Nature of non-farm activity or occupation	ns	c
7	Availability and quality of farm inputs	ns	c
8	The quality and adequacy of extension services	??	c

? *Farmers are selectively responsive to soil fertility-enhancing technologies despite this factor*

?? *There were differences between the farmer's stated understanding of the extension message and farmer practice.*

** *Statistically significant factor for adoption. More than 50% of the farmers are moderately to severely risk-averse.*

*** *Statistically significant factor for adoption. Male-headed households were more likely to adopt inorganic fertilizer innovations.*

ns Not statistically significant.

a: Literature review.

b: Elicited utility functions and mathematical risk programming.

c: Econometric analysis of data from a survey of 94 farming households in eastern Kenya; a binary choice model was used in the analysis.

The results of Muhammad (1996) suggest that the most important explanatory variables for adopting soil fertility-enhancing technologies are gender of the farmer and the farmer's attitude to risk. The finding that male-headed households had a higher probability of adopting high-cost soil fertility-enhancing technologies needs further investigation. It is possible that farmer gender is correlated with another variable such as farm size, level of formal education, nature of non-farm occupation, or availability and quality of farm inputs. If these variables are correlated with gender then an analysis excluding gender as an explanatory variable could change the level of significance of these other factors.

In Machakos District some 50% of the farms are managed by women (Rukandema 1984). Growing numbers of households are headed by women for most of the year, due to male migration seeking off-farm work. Nevertheless, men may retain the major decision-making responsibility for land use and crop planning, even when absent (Douglas 1993). In addition, women generally have less power in the rural community and therefore less access to extension advice and credit.

Farm households sometimes have to buy food during the hunger period (September to January) after the long dry season (Rukandema 1984). September, October and November are periods of very busy activity — land preparation, planting and weeding. People in poor families are at their weakest physically when they need most energy for field tasks. Such factors reduce adoption rates for new soil and fertilizer technology.

If research results indicate so clearly that modest, strategic use of inorganic fertilizers is a sound and profitable way of supplying nutrients to crops over most of Machakos District, could there be other reasons why many farmers are so hesitant to adopt this technique? From experiences recounted in the previous section, particularly those of the Kivoto mwethya group, poor farmer education on soil fertility management appears to be an important factor, and government extension services are having only a minor impact. Also, farmers who appreciate the need for soil fertility improvement but have little ready cash may still regard the education of a child, or other family needs, as of higher priority than purchasing fertilizers. There are several other possible reasons:

(i) Fertilizer is often not available locally in the required amounts at the start of a good, wet seasonal onset. Moreover, farmers' credit and cash resources are often low at the start of a new planting season.

(ii) Because of unstable fertilizer markets in East Africa, particularly now that privatisation and termination of Government subsidies are proceeding, prices can suddenly increase markedly, e.g. prices of N fertilizer in eastern Kenya increased 3–4-fold between 1990 and 1993. Farmers have also reported variations in fertilizer quality and incorrect labelling, e.g. ground rock phosphate labelled as triple superphosphate.

(iii) The extra labour for applying basal fertilizer at planting is required in a period of maximum farm activity (Waddington 1994) when there is a strong disincentive for involvement in further activities.

(iv) Farmers with low cash resources like to see their crops well established and be able to assess seasonal rainfall prospects before investing in fertilizer. When good establishment and soil moisture have been assured, e.g. 30 days after crop emergence, N fertilizer may be applied. This strategy of 'response farming' for reducing climatic and economic risks is quite appropriate for side-applications of N (Stewart and Faught 1984; Wafula et al. 1992). However, unless any existing soil P deficiency is corrected by an early application of readily available P, the effectiveness of late-applied N is likely to be reduced.

(v) Some farmers do not appreciate the complementary values of organic sources of nutrients, as in manure and composts, and of inorganic sources. Inorganic N, especially the nitrate form, is immmediately available to the crop, but the organic C supplied in boma manure has indispensable beneficial effects on soil structure, water infiltration and soil cation exchange. Whereas the N concentration of boma manure may be so low that it is not an effective source of plant-available N, it may still be a valuable source of P (Mokwunye 1980).

(vi) Because individual farmers' resources, farming systems and climatic environments vary widely, advice on the uses of inorganic fertilizers for each farm community needs to be carefully tailored after on-farm research in collaboration with an appropriate group of farmers (Waddington and Ransom 1995) .

WHAT CROP YIELDS CAN MACHAKOS SMALL HOLDERS ACHIEVE WITH FERTILIZERS?

Research shows that, with a high standard of crop husbandry in AEZ 4, applications of N 40–80 kg/ha to N-depleted soil should result in long-term average maize yields of about 2.8 t/ha (Keating et al. 1991; McCown and Keating 1992; Okalebo et al. 1996) compared with average yields of less than 1.0 t/ha currently obtained by most farmers. In this case, each kg of fertilizer N produces more than 20 kg grain, which would be quite profitable even when the purchase price of each kg of fertilizer N is 10 times the cost of 1 kg of maize (Probert et al. 1994).

Probert and colleagues (1994) also examined the most attractive options for risk-averse farmers in climatically less-favoured locations, using a crop growth simulation model and long-term records of daily rainfall. In almost every location studied these researchers concluded that, on N-depleted soils, application of some N fertilizer (albeit only N 10 kg/ha in some drier locations) would be an attractive option for farmers prepared to adjust their planting density and moisture conservation techniques accordingly.

This research assumes a good standard of crop management. It has not so far made allowances for the many contingencies small-scale resource-poor farmers may incur, e.g. unavoidable delays in ploughing and planting due to meagre equipment and low draught power, or delays in weeding due to shortages of family labour, or an unusually severe attack of stalk-borer which cannot be controlled before it substantially damages the crop. All these factors are known to reduce the expected crop response to applied nutrients (Keating et al. 1992, Waddington 1994, and many others). Such considerations might be expected to result in many farmers achieving only 50–70% of the yield found by the researcher, even when the relevant experiments were conducted on-farm with farmer management, but with an all-important addition of a few critical outside inputs such as insecticide, and cash for a little extra labour to ensure timely operations.

To summarise, two important points emerge. Firstly, farmers require a certain minimum level of resources, knowledge and management skills to be successful with the 'new technology' that research is advocating. They can then be convinced, as other farmer examples considered, to continue and to recommend the ideas to their neighbours. Secondly, because investment in fertilizer is cash-demanding, in a cash-scarce economy it is most logically used as part of an overall strategy of integrated nutrient management to complement nutrients available from home-produced organic sources. By balancing these varied inputs, a good farm manager can bring down the average unit cost of total nutrients applied and make most effect of the limited labour supplies of the household.

THE NEED FOR ADAPTIVE ON-FARM RESEARCH AND EXTENSION

REVIEWING THE EXPERIENCES OF farmers shows how difficult it becomes for poor households to adopt new technology involving some cash outlay, and so extract themselves from the 'poverty trap'. For some families, improvement of food security and financial status is virtually impossible without outside help. This highlights the need to involve farmers in better ways of maintaining soil fertility, before they descend too far into the 'trap'.

Extension services in most sub-Saharan countries are underfunded, and are provided by undertrained and underequipped staff. Yet wide experience shows that, without major extension effort, widespread adoption of a new technique is unlikely to occur, even though it has been well checked-out by on-farm research (Tripp 1991). That the linkage between national agricultural research and the extension arm is often too weak is also widely acknowledged (Tripp 1991; Low et al. 1991; Merrill-Sands et al. 1991). What can be done about this situation?

It is now generally appreciated that the problem must be approached from the farmer's viewpoint, whereas for many years the temptation has been for the researcher to look from a much more general viewpoint. Participation by the farmer in the research and evaluation process from the very beginning (as represented in Figure 4) is essential.

There are several options and decisions facing the small-scale farmer in a 'medium potential' area on the problem of maintaining soil fertility. Figure 5 shows some of the decisions to be made in integrated nutrient management on a typical mixed farm, with a rotation of crops and some livestock in a climatically risky area of eastern Africa.

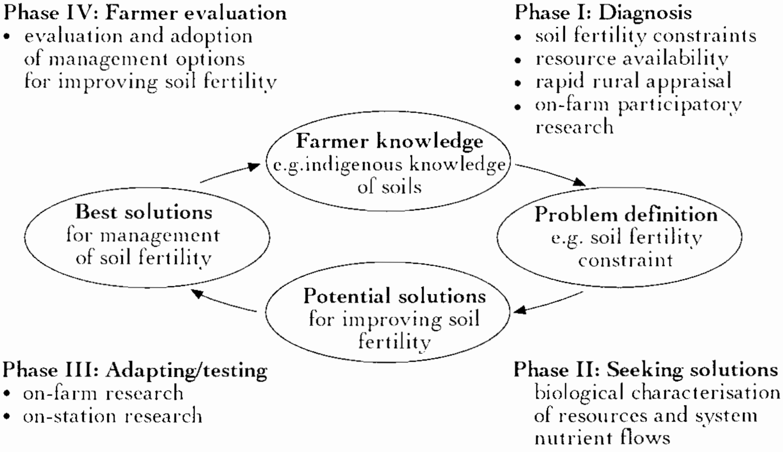

Figure 4. *The farmer-back-to-farmer paradigm applied to soil fertility research (Swift et al. 1994).*

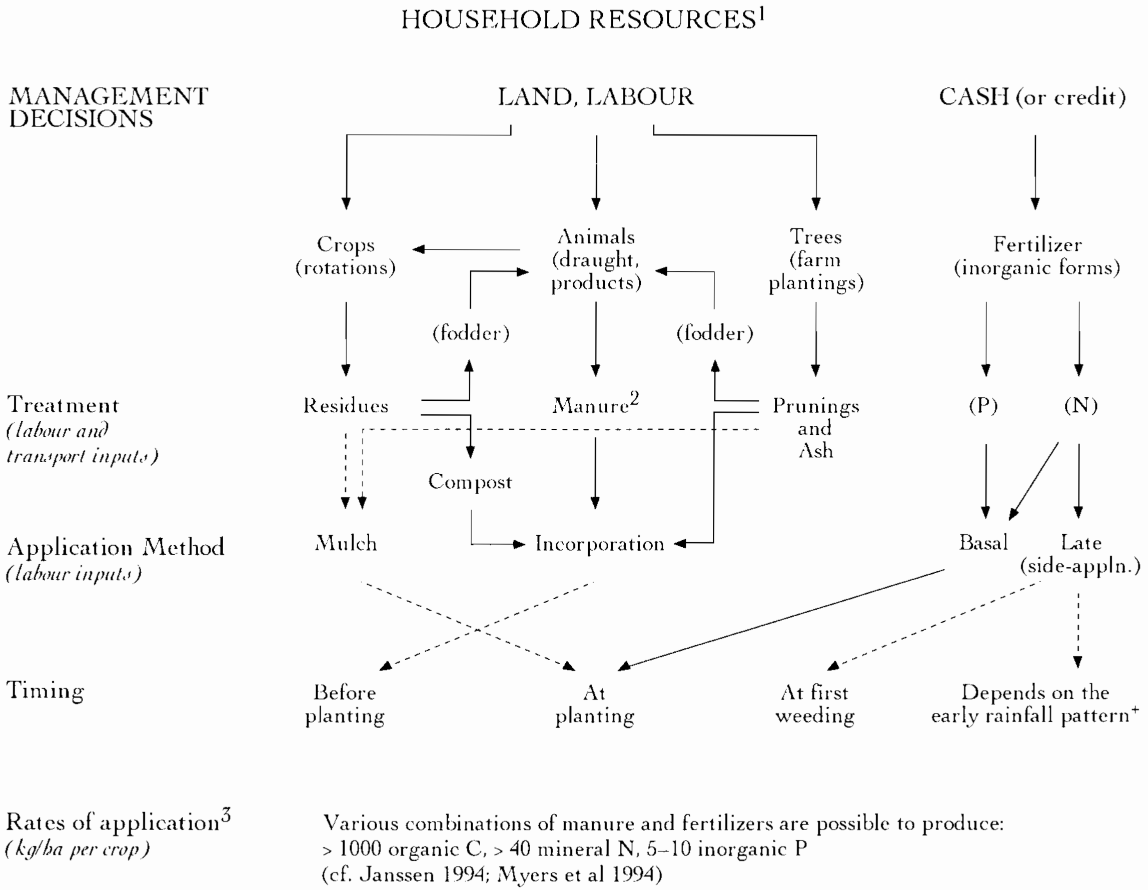

Figure 5. *Maintaining soil fertility in a typical Machakos mixed farming system: some possible management choices and interactions (using integrated nutrient management)*

Notes

1 a semi-arid mixed farming system.

2 method of storage is critical for manure quality; some manure may be sold for cash.

3 periodical and incremental adjustments may be made toward increased productivity.

+ response farming may be used (adjustments to fertilizer applications, rates and timing, after considering the date of seasonal rain onset and early seasonal prospects).

Such a matrix of management possibilities is bewildering to both farmers and extension agents. Tiffen et al. (1994, p. 276 and elsewhere) suggest that the problem of soil fertility maintenance will gradually be solved by farmers in Machakos, with only a modest amount of outside help. From the above considerations and experience so far, it is difficult to believe such a proposition. The problem of integrated nutrient management, based on few available resources, is too challenging to be resolved effectively and quickly by farmers unless they receive well-informed outside help — in the forms of on-farm research, education, extension and credit facilities. Delay in tackling the soil fertility problem creates greater intractability and allows soil degradation to continue. Moreover, the extension advice will have to be supplied in the form of options on management decisions aimed at gradually upgrading soil nutrient status and yield sustainability, which the household can consider and choose (McCown and Keating 1992; Waddington 1994).

In a recent paper, Pingali and colleagues (in press) discuss the factors involved in the successful adoption by Asian rice farmers of more efficient nutrient management techniques. They emphasise that existing blanket recommendations for fertilizer applications should no longer be used, if greater fertilizer efficency is to be achieved. Thus the challenge for future extension services becomes how to transfer knowledge and decision-making skills to farmers, rather than make generalised recommendations. This approach seems to be true of eastern Africa too (Waddington and Ransom 1995), though perhaps at a different level of sophistication. An important component is to understand the incentives that would cause farmers to be interested in acquiring and using technologies for better nutrient management. Pingali et al. stress that, for successful adoption, communication of extension messages must be in familiar terms and best done on a farmer-to-farmer level. A few progressive farmers will acquire the new management skills, and then be the source of expertise for other farmers in the same location or farming system. This Asian model might not be appropriate for all farmers in eastern Kenya, but the example discussed earlier, of the Kivoto mwethya group, shows that it can be adapted to work here too. Other examples of successful mwethya activities across Kenya (Cheatle and Njoroge 1993) show that the expertise-sharing model could have much merit.

Even in Kenyan high potential areas such as Kisii, declining soil fertility is a looming problem, despite high initial fertility (Smaling 1993). With competing demands, across the country, the lower potential areas in AEZs 4 and 5 might receive lower priority in the allocation of government funds for agricultural extension. Because of the large areas suffering fertility decline through eastern Africa, and the necessarily slow rates of adoption of changes in soil management, it is urgent that efforts are made to accelerate the process. The more desperate a farming household becomes, i.e. the deeper it descends into the poverty spiral or into drought, the shorter can the planning horizon of the farmer be. At these later stages of desperation, the household will have little thought for long-term conservation of soil resources, but will exploit remaining resources for whatever they will yield quickly.

Making an impact will require carefully designed on-farm research and extension, plus emphasis on training extension agents and on education and demonstration to create awareness of all the possibilities (Low et al. 1991). Opportunities vary with location. In AEZ 5, for instance, sustainable soil management options will logically lie toward organic inputs because livestock will remain an important part of the farming system, and the climatic risks for cropping are greater than in AEZ 4. In AEZs 3 and 4, emphasis shifts toward including the strategic use of inorganic N and P fertilizers in INM because of better crop response prospects and a sparser supply of organic manures.

CAN SIMULATION MODELLING OF CROP RESPONSES HELP?

In view of the many variables, the interactions of possible decisions in the mixed farming systems of medium potential areas, and the varying viewpoints of different farm households to decisions, sympathy with both farmers and extension advisors is possible. The task is formidable. However, recent developments in crop growth modelling bring potential help in the formulation of best soil management decisions (Carberry 1994; Keating et al. 1994).

A good example of possible development was shown by Probert and co-workers (1994). These authors used daily rainfall records (collected over 25–60 years) for seven locations in Machakos and Kitui Districts, together with assumed soil characteristics of a poor acrisol (0.4% organic C and 82 mm total available moisture capacity) or, alternatively, a better luvisol (1.1% organic C, 175 mm available moisture). They concluded that the addition of fertilizer N was a profitable long-term option for risk-averse farmers growing maize in all AEZs, on N-depleted soils similar to those assumed in their model. Low maize plant populations were optimal, 1.1 up to 4.4 plants/m^2, and additional N advocated by the simulations varied 10 to 80 kg N/ha, depending on location. Profitability of N fertilizer use was generally better in the short rains season than the long. The forecasts of optimum N requirements decreased from AEZ 2 (1100 mm pa rainfall) where it was N 40–80 kg/ha, through to AEZ 5 (500–600 mm/year), where it was N 10–40 kg/ha.

Several points should be remembered. Firstly, these are forecasts of economic attractiveness in the long-term, i.e. there will be some seasons when crop failure will occur. In AEZ 5, these will be around 20–30% of long rains seasons and about 10% of short rains seasons. For some, N applied in the drought season may be largely recoverable in the next season (Bennison and Evans 1968). As mentioned already, farmers in AEZ 5, where climatic risk is high, probably prefer to rely whenever possible on cheaper organic inputs to supply their crop N needs. Supply of boma manure is likely to be better here than in AEZ 4 and, because population pressure is lower than in western Machakos, the potential use of short-term fallows of planted N-fixing trees, e.g. Sesbania (Sanchez 1995), should be explored. The ultimate choice for the farmer is between the labour costs of 'organic' farming, and the cash purchase costs of inorganic N fertilizer or, more logically, deciding on an optimal combination of the two inputs (Waddington and Ransom 1995).

SOUTHERN AFRICAN EXPERIENCE IN ON-FARM RESEARCH

In a number of southern African countries, efforts have been made over the last 10–15 years to revitalise agronomic research, make it more relevant to farmers' immediate problems, and so improve the rates of adoption of new practices by farmers. Previous impact, particularly in agronomic operations and soil management, was modest. It was felt that better focusing of the research and closer collaboration with farmers and with extension staff are much needed. The experiences of this movement, especially in Zambia, Zimbabwe and Malawi, have been the subject of several reports associated with CIMMYT (e.g. Low et al. 1991; Tripp 1992; Waddington 1994).

Tripp (1992) emphasised that any planned changes in technology must be developed in close collaboration with farmers if they are to be successfully adopted. He reported that technology development for many farming systems has proved more difficult than envisaged:

> *'a great proportion of resources in on-farm research (OFR) has been devoted to tinkering with things like fertilizer or seeding rates whose results are either modest enough to escape the attention and interest of most farmers or require a more concerted extension effort. OFR is (now) built on a respect for farmers, their aspirations and knowledge, as well as on a sense of wonder at the complexity of their farming systems'.*

Low and colleagues (1991) examined the impact of 53 on-farm research initiatives in southern Africa. They list some of the factors found to have limited the impact of these initiatives on farming practices:

(i) the poor quality of the OFR — including superficial diagnosis, poor experimental work, inadequate analysis and a high rate of turnover of research staff;

(ii) a need for better integration of the adaptive OFR with broader component research;

(iii) a need for conditional or suboptimal recommendations for farmers whose resources do not enable them to plan to reach the 'best recommended' practices found by research;

(iv) communication problems between research and extension;

(v) a need for adjustments in extension approach (methods, content and training); and

(vi) problems of input supply and/or availability.

Merrill-Sands and colleagues (1991) listed in detail the managerial and institutional requirements for successful OFR and its extension to farmers. Clearly, adaptive OFR cannot always be successful (Low et al. 1991; Jeranyama 1992). To produce a substantial impact on the adoption of more sustainable soil fertility management practices in districts like Machakos is a major challenge for both research and extension.

Low and co-workers (1991) described three examples in southern Africa of coordination of on-farm adaptive research with extension arms of government agricultural departments. In Malawi, the Research Department at Chitedze controls and advises the Area Development Divisions which are responsible for both adaptive research and extension, working with individual farmers. This arrangement creates a heavy burden on the small adaptive research teams, and is not the best arrangement. In Zimbabwe, in contrast, the research department (DR&SS) and the extension service (AGRITEX) both conduct adaptive on-farm research. Their efforts, along with farmer effort, are coordinated by a committee for on-farm research and extension (COFRE); the arrangement is reasonably successful. In Zambia, the on-farm research is conducted by a specific Adaptive Research Program Team (ARPT) which is not responsible for extension. Extension is carried out by liaison officers (RELOs) who are familiar with all aspects of the research and become the conduit for a two-way information flow between researchers and farmers. Low and colleagues (1991) suggest that this last model is probably the best.

CONCLUSIONS

SOIL FERTILITY RESEARCH IN eastern Africa has changed its focus markedly since it began in the 1930s. The changes are partly in response to the major demographic changes putting increased pressure on the soils of the croplands. Soils have become depleted through more intensive cropping, little or no restorative breaks in the rotation, and continuing low external inputs of nutrients and organic materials. The main priority now is to improve and restore fertility, while continuing production of vital food crops for as long as possible in the rotation.

Early research sought to maintain fertility by restorative vegetative fallows and inputs of organic manures. Then, as the opportunities for using these methods gradually decreased, there followed a period of intensive work searching for economic responses to imported inorganic fertilizers. Current researchers are finding, at least in the areas of medium agricultural potential such as Machakos, that sustainable cropping systems which are both acceptable to small-scale farmers and scientifically sound are likely to involve both organic and inorganic inputs. This approach of 'integrated nutrient management' aims to optimise the use of locally produced organic inputs to provide both nutrients and maintain soil organic C. Other household demands and the constraints of available household labour and equipment, essential in handling and processing these bulky materials, will limit the utilisation of organic inputs. These organic sources will not be sufficient to maintain fertility in most farm situations, though the supply might sometimes be boosted through agroforestry. Therefore current research strives, with the aid and collaboration of farmers, to design ways of combining the more expensive, but labour-efficient, inorganic nutrients from externally purchased fertilizers with inputs of local organic materials, both to satisfy crop demands and maintain soil fertility.

Current research has been aided by farming systems studies and farmer-back-to-farmer ideas; it is motivated by the urgent need to boost food crop production if further ecological and human disasters are to be avoided. Computer technologies of crop simulation modelling and geographic information systems are now available to assist on-farm researchers with very valuable analyses of the feasible options available to farmers, using data on resources and climatic expectations at local level. This welcome focusing and improved capacity of current research will have the desired impact on farming practices only if it can be closely linked with continuing extension effort to convey appropriate messages to farmers, to demonstrate, discuss and educate on the feasible options before them. Also, if external inorganic inputs are to be used efficently, they will have to be made available to farmers by a much better and more reliable infrastructure of providers and credit sources.

This has not existed previously for small-scale resource-poor farmers in the medium potential areas of eastern Africa.

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