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Maize Based Cropping Systems in the Subhumid Zone of East and Southern Africa

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Introduction

The subhumid zone accounts for 38% of the total land area of Sub-Saharan Africa (SSA) (Deckers, 1993). The subhumid zones of Southern Africa, Central, East and West Africa have a variable growing season length of 180 to 270 days. The rainfall pattern in the Southern Africa region is unimodal with a range of 800 to 1200 mm per annum. The rainfall pattern in East and Central Africa is bimodal characterized by short and long rainy seasons. In the unimodal subhumid areas, rainfall pattern is highly variable in terms of start of the season and amount of total rainfall received in the season. This high variability in the amount of rainfall received is associated with mid-season droughts and variable crop yields especially for maize. The zone is commonly referred to as 'the bread basket of Africa' and it is characterized by high variability in soil types, rainfall, altitude and climate. High population densities are

found in this zone resulting in various degrees of agricultural intensification.

The major soil types in the subhumid zone of East, Central and Southern Africa are a result of parent material, age and past and current climatic conditions. The main soil types found in this zone are shown in (Table 3.1).

Table 3.1. Distribution of major soil types in the subhumid zone of Sub-Saharan Africa

FAO classification	USDA Taxonomy	Area in km^2	% coverage of total area	Areas of major occurrences
Ferralsols	Oxisols	1847898	32	Zaire, Angola, Zambia, Rwanda, Burundi, Uganda, Southern Sudan
Acrisols	Ultisols	530603	9	Subhumid West Africa, Southern Guinea, Togo, Benin, Nigeria, Central, Cameroon, Côte d'Ivoire
Lixisols	Alfisols	1666151	29	South-East Africa, Madagascar
Nitisols	Paleustults Paleulistalfs	435931	8	Ethiopia, Kenya, Tanzania, East Zaire
Arerosols	Psamments	580433	10	N. Senegal, N. Mali, Southern Niger, E. Sudan, S-E Zaire, Botswana, Angola
Vertisols	Vertisols	158785	3	Sudan, Tanzania, Ethiopia
Others	Various	301258	9	Limited occurrences
Total		5753564	100	

Source: Decker, (1993) and Sanchez and Logan, (1992)

With the exception of Uganda, Burundi and Rwanda where bananas are the main staple food, maize is the main staple food crop in East and Southern Africa, with an estimated land area of about 15.5 million ha (Pingali, 2001). Rosegrant *et al.* (1996), estimated that the demand for maize in this region of Sub-Saharan Africa would rise from 21.3 million tonnes per year in 1990 to over 52 million tonnes in 2020. Compared to

the minor cereals such as millet and sorghum, maize is a main staple food due to its:

- Higher grain yields compared to millet
- Requires less processing
- Not susceptible to bird damage when compared to sorghum
- Maize crop has wide plasticity; it is grown in a wide range of environments
- Maize is also a cash crop with ready markets within the region
- High input responsiveness
- Easy to grow agronomically using hand labour and tools
- High suitability for many agro-industrial processes

This chapter will discuss the soil fertility management in the subhumid zone in relation to soil biology, then discuss the main maize cropping systems such as intercropping and maize monocropping systems and soil fertility management issues in these systems. Maize-livestock interaction will be discussed since manure is a predominant source of nutrients for most maize cropping systems in the subhumid zone. Issues on integrated resource management including organics combined with inorganics are also discussed. A synthesis is presented including some highlights of what works and some indication of innovations for future research.

Soil Fertility Constraints

Soil constraints in the subhumid tropical Africa can be divided into two major types: soil chemical and physical constraints. The chemical constraints include low nutrients reserves, low cation exchange capacity (CEC), aluminium toxicity, soil pH and phosphorus fixation as suggested by Sanchez and Logan (1992). The physical constraints to increased soil productivity are limited rooting depth, low water holding capacity and susceptibility to soil erosion, soil crusting and compaction.

Low nutrient reserves and cation exchange capacity

About 55% of the soils in the subhumid zones of SSA have inherent low nutrient reserves (Sanchez and Logan, 1992). For instance, net annual losses of more than 30 kg N/ha have been estimated for some Eastern and Southern African countries (Smaling, 1993; Stoorvogel *et al.*, 1993). This constraint is especially found in highly weathered soils such as Oxisols and Ultisols. These and other soils such as the sandy Psamments have limited capacity to retain and to supply cations and other major nutrients such as Nitrogen (N), Phosporus (P) and Sulphur (S) required by plants, with the exception of Vertisols and Alfisols. Most of these soils are extremely nutrient-depleted and crop production can only be

sustained by regular addition of external nutrients and by proper soil organic matter management.

Nitrogen deficiency

Nitrogen is the key nutrient for crop production. This element is the most mobile and also the most easily exhausted nutrient in the soil. Smallholder farmers rely on natural fallow periods and use of leguminous crops to restore soil nitrogen status (Nye and Greenland, 1960; Kwesiga and Coe 1994; Hartermink *et al.*, 1996). However due to high population density and land pressure in subhumid tropics, long fallow periods are no longer sustainable. To sustain high crop yields in intensive and continuous crop production system, nitrogen fertilizer input is required. This is particularly so in commercial farms in Kenya and Zimbabwe. As nitrogen is the most costly nutrient and its availability can also be a problem to smallholder farmers, efforts should be made to increase efficiency of nitrogen fertilizer use (that is reported to be very low in most smallholder farms (Palm *et al.*, 1997)) and develop an integrated nitrogen management system that can fully exploit biological nitrogen fixation and other organic sources of N in various production systems.

The potential N contribution from biological nitrogen fixation (BNF) and other organic inputs can be very significant in maize production systems. The beneficial effects come mostly from nitrogen in the crop residues and tree prunings. Nitrogen contribution by grain legumes, however, may be small due to N removal in grain at harvest compared to contribution from prunings of tree legumes and it is also usually higher from sole than intercropped legumes. Sole grain legumes in rotation with maize can contribute between 40-70 kg N/ha to the subsequent crops. Inclusion of legumes as green manure, cover crops and improved fallows in maize based cropping systems offers additional benefits such as weed suppression, soil erosion control and soil structure amelioration. The organic input can also provide carbon sources to microbial biomass and increase microbial activity (unlike inorganic N fertilizer) and assist in maintaining or increasing soil organic matter status of the soil.

Phosphorus deficiency, fixation and soil acidity

Apart from nitrogen, phosphorus is a major element limiting crop production in the tropics (Buresh *et al.*, 1997) especially in East Africa. Phosphorus problem is exacerbated by fixation by aluminum (and iron) in the vast majority of soils in the zone especially Ferralsols, Acrisols and Nitisols (Buresh *et al.*, 1997). This problem may be overcome by application of small amounts of P and other P strategies reviewed by Buresh *et al.* (1997).

Another related problem of Ferralsols, Acrisols, Lixisols and Nitisols is the pH dependency of the nutrient storage capacity. Regular

application of lime and organic inputs into the soil would raise soil pH and reduce phosphate fixation and aluminium toxicity. The action of organics is attributed to production of organic acids during decomposition that block or react with P fixing sites (bind aluminum reducing its saturation and thereby reducing soil acidity) (Wong *et al.*, 1995; Nziguheba *et al.*, 1998). In addition, application of organic inputs especially those of high quality may lead to increase in soil microbial biomass and thus may increase nutrient availability.

Poor structural stability and induced hard pan formation

The structural stability of many soils in subhumid zones, particularly the Alfisols, is very low and the aggregates are easily destroyed on watering by rainfall or irrigation water. The break down of main aggregates is due to entrapped air and differential swelling called sling, which results in formation of micro aggregates. Such crusting reduces aeration and infiltration of rainwater. Cultivation of such soils when wet leads to formation of hard pans in the plough layer. Low organic matter content and low clay content (3 to 12%) are some of the conditions that lead to crusting and compaction.

The consequences of hard crusting and compaction lead to:

- Increased runoff and erosion rates
- Restricted root growth
- Seed germination impairment
- Decreased crop yields

Application of organic inputs to the soil may lead to higher soil organic matter (SOM) content and increased microbial population leading to more aggregate stability which will increase infiltration rate and reduce erosion losses of soil and nutrients. Despite the belief that soil organic matter contents cannot be replenished in tropical soils under cultivation due to the 'fast rate of oxidation', there are examples where SOM has been increased depending on the amount of organic residues returned to the soil. For example Bache and Heathcote (1969), demonstrated that addition of cattle manure at 2 t/ha for 15 years led to small increases in soil carbon (from 0.24 to 0.43%) and N (from 0.021 to 0.034% N content at Samaru, Nigeria. At Kabete, Kenya however, addition of 10 t/ha of cattle manure combined with return of all crop residues failed to prevent a decline in the SOM contents in an Alfisol cropped annually to maize and beans (Kapkiyai *et al.*, 1997).

Soil moisture is a major constraint to increased crop productivity especially in subhumid zones. Soils such as Oxisols, Ultisols and Psamments have limited ability to hold water due to their low clay content. Associated with this property is the occurrence of soil erosion especially on Psamments and some Alfisols. Application of organic inputs may lead to high SOM and increase the water holding capacity of these soils.

Maize Cropping Systems

Due to high variability in climatic conditions, diverse soil types, population density and socio-economic factors, maize cropping systems are very diverse in this zone. They range from intercropping systems for risk management and efficient use of land and labour resources to solecropping systems. Solecropped maize can be produced from high fertilizer inputs (commercial maize production especially in Kenya and Zimbabwe) to solecropped maize rotated with legumes or maize produced with integration of organic and inorganic inputs.

Maize sole cropping

As mentioned earlier, maize is the main staple food in the subhumid tropics of Africa. During the colonial era, farmers were encouraged to solecrop maize instead of the traditional practice of intercropping. A case in point was in Zimbabwe where the *master farmer scheme* by colonial extension system encouraged solecropping and rotation of maize with legumes for farmers to get a master farmer certificate. The advantages of solecropped maize were ease of mechanization, weed control and use of fertilizers.

This extension practice of solecropping led to the use of the mouldboard plough. The continuous use of the plough for the same ploughing depth led to the formation of hard pans with its associated problems. The soil fertility maintenance practice under solecropping was rotation of maize with grain legumes or green manures. Manure from livestock was also applied to maize as a source of nutrients. Where subsidies to farm inputs were available, inorganic fertilizers were used to maintain high maize yields. The use of inorganic fertilizers on maize has been largely uneconomic in some countries since the removal of government subsidies (Benson, 1997). This led to continuous cropping without inorganic inputs resulting in negative nutrient balance for N, P and K in most countries (Smaling, 1993). This led to the search for more sustainable technologies such as crop rotations, improved fallows, biomass transfer, hedgerow intercropping and integrated nutrient management techniques which combine inorganic and organic sources of nutrients.

Commercial monocropping maize system

Commercial agriculture based on high level mechanization, huge amounts of inorganic fertilizer inputs and agrochemicals were introduced in subhumid Africa since the advent of the green revolution. This was particularly important for maize with the introduction of high yielding hybrid varieties. Commercial farmers especially in Zimbabwe and Kenya

have adopted the green revolution in maize production. It is estimated that 50% of the annual global food supply will come from the application of inorganic fertilizers alone (Dyson 1995). Maize yields up to 10 t/ha have been obtained with inorganic fertilizer inputs of 600-1000 kg of nutrients per ha. This has been responsible for meeting half of the national maize requirements and also for export markets. While productivity of this type is very high, its sustainability in terms of soil biology and productivity and economic viability is starting to be questioned.

Literature review by Bekunda *et al.* (1997) showed that continuous application of inorganic fertilizers over the long term led to decrease in maize yields. Similar results have been observed in the long term experiments at the National Agricultural Research Laboratories, Kenya (Kapkiyai *et al.*, 1999). The reasons for this decline could be due to the following:

- Soil acidification by fertilizers, especially ammonium-based fertilizers
- Mining of nutrients via harvest (more nutrients in grain and stover than added through fertilizer application)
- Leaching of N fertilizer
- Declining of soil organic matter

Mineral fertilizers should be part of the overall strategy to restore soil fertility and increase crop productivity in subhumid Africa. However exclusive use of inorganic fertilizers will not solve the soil mining problems considering the fact that the use of such a nutrient source does not replenish the declining SOM that is crucial to the sustainability of agriculture especially for the smallholder farmers. As such an integrated approach of using inorganic fertilizers with organic inputs should be promoted to ensure sustainability of the cropping systems.

Maize intercropping systems

Maize intercropping systems are very common in large areas of East and Southern Africa. Maize and beans (*Phaseolus vulgaris*) are predominant in East Africa. In Southern Africa, maize is intercropped with cowpeas, groundnuts and bambara nuts to a less extent. The importance of intercrops is widely recognized by farmers. This arises from the stabilizing effect of crops on food security, enhanced use efficiency of land, water and labour and risk aversion in case of crop failure. The role of intercrops in soil fertility maintenance is also documented. The low plant densities of legumes found in most intercrops means that they can input modest amounts of N and organic matter each year to maintain soil fertility. However, because they do not take away land from cereals, farmers may be willing to use them every year so that the aggregate effect may be enhanced land productivity.

Grain legume intercropping systems

Intercropping of grain legumes generally results in the legume deriving a greater proportion of its N from N_2 fixation than when grown alone, but legume dry-matter production and N accumulation are usually reduced because of competition from the companion crop (Table 3.2) so that the overall amount of N_2 fixed is less than that of sole crop of a legume. Cowpea intercropping was advantageous with maize or millet in seasons with adequate rainfall, but the cowpea competed strongly with the cereal crop for soil water when rainfall was limiting (Shumba *et al.*, 1990). One notable exception again is traditional pigeonpea, which has a phenology complementary to that of most cereal crops. Its initial aboveground growth and development is very slow, hence there is little direct competition between the two crops (Natarajan and Mafongoya, 1992). The long duration and its ability to root deeply allows the pigeonpea to grow on after the companion cereal crop has been harvested, utilizing residual moisture in the soil. However, although sole pigeonpea produced clear residual effects in the growth of subsequent maize, the residual effects of maize – pigeonpea intercrops were not substantial (Kumar-Rao *et al.*, 1983, Kumar-Rao and Dart, 1987), presumably because of reduced inputs of N. Despite claims for substantial *transfer* of N from grain legumes to companion cereal crops, the evidence indicates that benefits are limited and largely due to *sparing* effects (Giller *et al.*, 1991). Benefits are more likely to accrue to subsequent crops as the main transfer pathway is due to root and nodule senescence and fallen leaves (Ledgard & Giller, 1995).

Table 3.2. Biomass and nitrogen accumulation of green manure crops in Malawi

Legume crop	Cropping system	Age in weeks	Dry matter t/ha	N accumulation kg/ha
Crotalaria	Sole	16-24	2.6	50-190
ochroleuca	Intercrop	16-24	1.5	38
Mucuna pruriens	Sole	13-18	2.9	60-290
	Intercrop	13-18	3.6	105
Cajanus cajan	Sole	35-52	4.8	75-200
	Intercrop	35-52	2.5	105
Mucuna	Sole	52	3.3	131
	Intercrop	52	0.4	16
Sun hemp	Sole	52	15.0	ND
	Intercrop	52	5.0	ND

Source: Kumwenda *et al* (1996)
ND = not determined

Relay intercropping maize systems

Intercropping and relay cropping of legume green manures or trees have the advantage that crops are still produced while organic material is produced for soil amendment. The obvious disadvantages are that the green manures or trees may compete with the crops, and that the amounts of organic material produced are generally less as compared to when they are produced alone. Thus, whether intercropping with green manures and trees is advantageous depends on this balance and the costs and benefits involved. The net benefits may however, vary significantly between sites and seasons, depending on the availability of water and nutrients, and the unpredictable nature of the interactions between the green manure and the crop adds a risky complication. Relay planting can reduce the likelihood of competition with the crop where rainfall is limited, with the production of the green manure restricted by its ability to use residual water after the main cropping season.

Hedgerow intercropping maize system

Hedgerow intercropping (also referred to as alley cropping), developed by scientists at the International Institute for Tropical Agriculture (IITA) in the early 1980s, has been very useful in developing a better understanding of tree-crop interactions (Vanlauwe *et al.*, 1996). It consists of growing food crops in the alleys formed by hedgerows of multipurpose trees and shrubs (MPTs) that are usually N_2 fixing. The hedgerows are cut back (lopped) and periodically pruned during the cropping season to prevent shading of the companion crops. The prunings provide nutrients when incorporated into the soil as green manure or spread on the soil surface as mulch (Kang *et al.*, 1990). By retaining woody perennials in crop production fields on a continuing basis, alley cropping simulates the role of fallow in soil fertility regeneration in shifting cultivation (Nair, 1993).

Though alley cropping technology has generated a lot of data to date, it seems that the system performance is location-specific and greatly influenced by the choice of tree species and the type of management adopted (Mugendi *et al.*, 1999a;b). Generalizations and extrapolation of results to seemingly similar environments is, therefore, difficult and as well misleading (Nair *et al.*, 1999). In order to assess the long-term performance of alley cropping, Rao *et al.* (1997), reviewed the results of 29 trials, mostly with small plots, conducted for four or more years over a wide range of soils and climates across the tropics. The results showed both positive and negative effects of alley cropping on crop yields. In the semiarid sites, only two of ten studies gave substantial yield increases. In subhumid environments, significant positive yield responses were observed in seven out of eleven studies while in the humid tropics, maize and taro did not benefit from hedgerow

intercropping in four out of eight trials, though bean and cowpea yield invariably increased.

Low biomass production of the hedgerow tree species (2 to 3 Mg ha/yr) and competition of hedgerows for water with crops are the major drawbacks limiting the potential of prunings to improve fertility and productivity of soils in the water-limited areas (Ong *et al.*, 1991; Rao *et al.*, 1991; Mugendi *et al.*, 1997; Mathuva *et al.*, 1998). Inadequate water limited the response of crops even though alley cropping improved soil fertility in certain sites of the semiarid tropics. In such cases, a biomass transfer (cut-and-carry) system has been proposed as a more beneficial system than alley cropping (Jama *et al.*, 1995). In certain other sites, especially in the subhumid zone, where hedgerow intercropping has been demonstrated to be a viable technology, issues revolving around labour required in the intensive management of the tree hedges have continued to be a disincentive to the adoption of the technology (Kang *et al.*, 1990; Mugendi *et al.*, 1999a;b). An exception may be on steeply sloping lands, where hedgerows can be planted on contours to help prevent soil erosion (Young, 1997).

Another form of hedgerow intercropping is the one that has recently been developed by scientists at the Makoka Research Station (ICRAF, 1997) in southern Malawi known as mixed intercropping system. The system allows continuous cultivation without fallowing. The soils in southern Malawi are mainly deficient in nitrogen, but fallowing is precluded because of small land holding due to high population density. High population density and extremely small farm size also preclude cattle production, thereby eliminating the potential use of manure as nutrient input. Mixed intercropping system that integrates *Gliricidia sepium* trees grown in furrows with maize occupying the ridges has been developed to address this problem of nitrogen deficiency. The system ensures that maize population is the same as in the sole cropping system. The trees are coppiced and the prunings applied as green manure to the maize ridges. The results so far indicate that use of *Gliricidia* green manure can greatly increase maize yields over those obtained through continuous sole cropping. The beneficial effect of the mulch was significant in four of the five cropping seasons, when maize yields from intercropped treatments were substantially higher than those from control plots (both with and without the addition of mineral fertilizer) as exemplified by the results of the maize grain yields in both 1996 and 1997 (Table 3.3). Lower yields in 1997 were attributed to excessive rainfall and waterlogging. Topsoil ammonium, nitrate and total inorganic nitrogen (ammonium + nitrate) were significantly correlated with maize grain yields in both 1996 and 1997. For both seasons combined, pre-season inorganic nitrogen was correlated with maize grain yield.

Table 3.3. Maize grain yield with and without *gliricidia* intercropping and fertilizer nitrogen in 1996 and 1997 at Makoka, Malawi

	1996	1997		
Fertilizer added (kg N/ha)	No. tree	Tree	No. tree	Tree
	Maize grain yield (t/ha)			
0	1.0	4.8	0.4	3.5
24	3.5	6.1	2.0	3.6
48	4.2	6.7	2.1 ·	4.3

LSD (0.05): N rate = 0.45, tree biomass = 0.36 for 1996

LSd (0.05): N rate = 0.50, tree biomass = 0.41 for 1997

Source: ICRAF (1997)

Intercropping and relay cropping of legume green manures or trees have the advantage that crops are still produced while organic material is produced for soil amendment. The obvious disadvantages are that the trees may compete with the crops and that the amounts of organic material produced are generally less than when the land is devoted to soil improvement. Whether intercropping with green manures and trees is advantageous depends on the balance between the benefits and the costs. The net benefits may vary significantly between sites and seasons, depending on the availability of water and nutrients and the unpredictable nature of the interactions between the green manure and the crop adds a risky complication. Relay planting can reduce the likelihood of competition with the crop where rainfall is limited, with the production of the green manure restricted by its ability to use residual water after the main cropping season.

Green manure and cover crops

Many leguminous species are now grown as green manure and cover crops for erosion control, weed suppression and for soil fertility restoration. The advantages associated with the use of cover crops include:
(1) enriching the soil with biologically fixed N,
(2) conserving and recycling soil mineral nutrients,
(3) providing ground cover which helps minimize soil erosion, and
(4) requiring little or no cash input (Franzluebbers *et al.*, 1998).

Biological N contribution is probably the main reason why farmers include legume cover crops in cropping systems (Jeranyama *et al.*, 1998).

A legume cover crop may contribute N to a subsequent non-leguminous crop, reducing N fertilizer needs by 100 kg N/ha and more in some cases (Hesterman *et al.*, 1992). It is however, also worth noting that cover crops can also deplete the soil moisture necessary for grain production in semi-arid areas (Badaruddin and Meyer 1989) and can compete for light and nutrients with the revenue crop (Badaruddin and Meyer 1989). Farmers can therefore take advantage of the beneficial effects of green manure and cover crop species to maintain and improve their farm productivity.

Many fast growing leguminous species such as mucuna (*Mucuna pruriens*), soya beans (*Glycine max*) and various species of the *Phaseolus* family can be especially useful as green manures and cover crops. Gitari *et al.* (2000) studied the performance of *Mucuna pruriens* and *Crotolaria ochroleuca* green manure legumes under different combinations with crops in Mount Kenya region. In the long rain season, maize grain yield was 6.5 and 3.1 t/ha, where only legume residue was used as a source of N at Karurina and Gachoka sites, respectively. This is compared with farmer practice (use of different combinations of inorganic fertilizers) grain yield of 3.5 and 2.7 t/ha for the same sites. In general, maize grain yields at both sites were highest in plots where legume green manure was used alone or in combination with either animal manure or mineral fertilizers. In a similar study carried out by Kamidi *et al.* (2000) at Matunda in Western Kenya, legume green manures tended to boost maize and bean grain yields. The green manures planted were velvet bean (*Mucuna pruriens*), soybeans (*Glycine max*), dolichos (*Lablab purpureus*), sunnhemp (*Crotalaria ochroleuca*) and cowpeas (*Vigna unguiculata*). The yields from plots under legume cover and half the recommended rates of inorganic fertilizers recorded significantly higher grain yields (velvet bean- 7.2 tha^{-1}, soybeans- 6.9 tha^{-1}, sunnhemp- 7.4 tha^{-1}, cowpeas- 7.1 tha^{-1} and dolichos- 6.6 tha^{-1}) than that obtained from farmer practice (4.8 tha^{-1}). In this same study Mucuna had the highest ground cover (72%) followed by *Crotalaria* (63%) and *Lablab* (54%). Soybeans and cowpeas gave the lowest ground cover (32% and 38%, respectively). The groundcover offered by these green manures greatly reduced soil erosion especially during the long rain season as noted by Gachene *et al.* (2000).

Increasingly the traditional nutrient sources for soil fertility management are produced in insufficient quantities and quality to meet maize crop demands (Palm *et al.*, 1997). Alternative higher quality sources must be found but there must also be niches on farms, or the vicinity, where they can be produced. Leguminous plant materials provide higher quality organic inputs to meet N demands, if not P, but incorporating non-food legumes in the farming systems require a sacrifice of space or time that is normally devoted to crop production. Additional labour requirements for planting, transporting and incorporating these

materials is also high (Jama *et al.*, 1997). As such legumes for soil fertility improvement have not been widely adopted by farmers (Jama *et al.*, 1998). The economic and social trade-offs of improved soil fertility using legumes and other high quality organic materials must be properly assessed in comparison to that of the management of crop residues and animal manures. Moreover access to seed, incidences of pests and diseases as well as competition for water, light and nutrients between the crop and the green manure/ cover crops need to be properly understood inorder to make this technology sustainable. .

Grain legumes in crop rotations

The role of leguminous crops in maintaining soil fertility is well recognized but has too frequently been overestimated. Mixed intercropping of cereals with herbaceous legumes such as groundnuts (*Arachi hypogaea*), soybeans [*Glycine max* (L) Merr] and *Phaseolus* beans or tree legumes such as pigeonpeas (*Cajanus cajan*) has been advocated (MacColl, 1989). Tropical grain legumes can certainly fix substantial amounts of N given favourable conditions, but the majority of this N is often harvested in the grain. Legumes such as soybean that have been subject to intense breeding efforts are very efficient at translocating their N into the grain, and even when the residues are returned to the soil there is generally a net removal of N from the field (Giller *et al.*, 1994). Some promiscuous soybean varieties that are leafier, have a greater potential to add N to the soil, and are potentially more appropriate for cultivation by smallholder farmers than the recommended varieties grown on commercial farms in Southern Africa (Mpepereki *et al.*, 1996). Soybean residues at harvest are lignified (10% lignin) with C/N ratios around 45:1 and these tend to immobilize N when they are added to the soil (Toomsan *et al.*, 1995). By contrast, groundnut (*Arachis hypogaea* L.) residues can contain >160 kg Nha^{-1}, are less lignified (5% lignin), and are rich in N, as the crop is harvested while still green.

If returned to the soil, groundnut residues can easily lead to doubling of maize yields (Snapp *et al.*, 1998). For many years rotation of maize with groundnut has been the most common legume and cereal crop sequence on smallholder farms in sub-humid parts of Zimbabwe (Shumba, 1983; Metelerkamp, 1987). Under favourable management and when groundnut residues are incorporated on sandy soils, groundnut in rotation can double the yield of the following maize, particularly when the maize is grown with little or no N fertilizer (Mukurumbira, 1985). There is growing realization that on most smallholder fields where the grain and biomass yields from grain legumes are very poor and where both the grain and most of the legume stover are removed from the field, there may be little or no net N contribution

by the legume to the soil and so little improvement in yield of the subsequent maize (MacColl, 1989).

The exceptions to this rule of large losses of nutrients in grain harvests are the longer duration grain legumes such as pigeonpea [*Cajanus cajan* (L) Millsp.] and varieties of cowpea [*Vigna unguiculata* (L.) Walp. ssp unguiculata], which may lose a substantial amount of biomass in the form of roots and leaves that fall before harvest (Giller & Cadisch, 1995). A sole pigeonpea crop drops up to 40 kg N/ha in fallen leaves during its growth (Kumar-Rao *et al.*, 1983), and its small harvest index means that a relatively large proportion of the fixed N remains in the field which can give a substantial benefit to subsequent crops. In addition, the rooting habit of pigeon pea has an added advantage of mining nutrients from deeper soil horizons thereby enriching the upper surface of the soil through leaf fall and litter decomposition (Van Noordwijk, 1989; Mekonnen *et al.*, 1997).

But virtually all the information that is available on legume N contributions is from research conducted on experimental stations where the crops have been adequately fertilized with P and other nutrients, and often irrigated. As biomass and yields of sole-cropped grain legumes under smallholder conditions in Africa are often small (<500 kg/ha of grain), the amounts of N_2 fixed are barely significant. For example, in the Usambara Mountains in northern Tanzania, where bean (*Phaseolus vulgaris* L.) is the staple grain legume, most farmers' crops lacked nodules because of severe P deficiency, and amounts of N_2 fixed were estimated to be 2 to 8 kg N ha^{-1} (Amijee and Giller, 1998). Amounts of N_2 fixation by grain legumes also can however be severely constrained by drought.

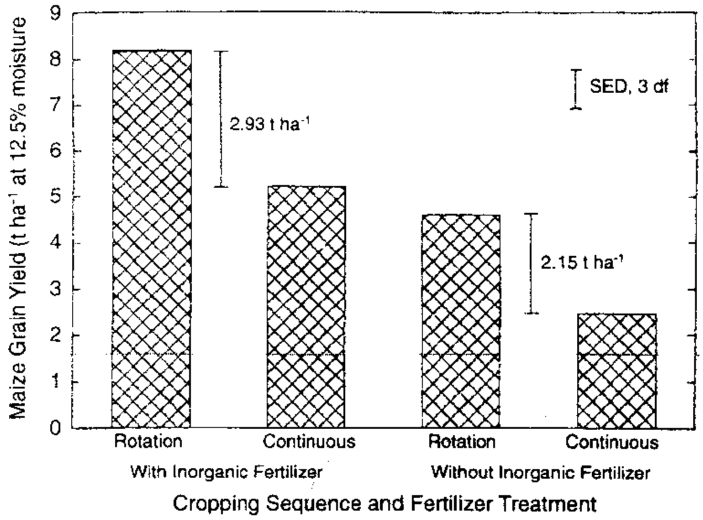
Improved fallows

Traditional shifting cultivation such as chitemene and fundikila (in Zambia) and other forms of shifting cultivation with intermittent long natural fallow periods were adequate to maintain soil fertility and crop production. However, the increasing demand for land as a result of population increase has reduced the fallow periods from about 5 to 2 years making the system unsustainable. Planted tree fallows with leguminous trees or shrubs that accumulate N in the biomass through biological nitrogen fixation (BNF) and capture of subsoil nitrogen (otherwise unutilized by crops) have been found to be an excellent option to replace natural fallows and increase maize yields on N deficient sites (Kwesiga and Coe, 1994).

Short-term fallows of leguminous trees and herbaceous cover crops can provide a practical means of nutrient cycling when grown in rotation with cereal crops. Two-year tree fallows of sesbania [*Sesbania sesban*) (L) Merr.] or tephrosia (*Tephrosia vogelii* Hook. F.) have replenished soil

N to levels sufficient enough to grow three subsequent high-yielding maize crops in N-depleted, but P-sufficient soils in Southern Africa (Kwesiga and Coe, 1994; Kwesiga *et al.*, 1998; Figure 3.1). In general, woody fallows accumulate larger N stocks than herbaceous ones because of their larger and continuing biomass accumulation than those of herbaceous fallows do. The residual effects of tree fallows are therefore longer than herbaceous fallows.

Figure 3.1. The grain yield of maize with and without fertilizer in the fourth year of a long-term trial involving rotations with groundnuts, Domboshava, 1995/96



Rotation = Maize after groundnuts in a maize/maize/gnuts/maize rotation
Continuous = Fourth year of continuous maize
With inorganic fertilizer = 92 kgN. 17 kg K ha^{-1} each year on maize, no fertilizer on groundnuts
Without inorganic Fertilizer = No fertilizer on maize for four years, no fertilizer on groundnuts

Source: Snapp *et al* (1998)

There is evidence that non-N-fixing trees and shrubs of the genus *Senna* and *Tithonia* accumulate as much N in their leaves as N-fixing legumes presumably because of their greater root volume and ability to scavenge nutrients from the soil (Szott *et al.*, 1991; Garrity and Mercado, 1994, Gachengo, 1996). But it is important to note that these non-fixing trees are only cycling the N present in the soil, not adding inputs to the system, as happens via BNF in woody and herbaceous leguminous fallows. Non-fixing trees and shrubs can only be considered to be N inputs when biomass is transferred from one field to another.

Tree roots are often able to capture nutrients at depths beyond the reach of most crop roots. This can be considered an additional nutrient input in agroforestry systems when such nutrients are transferred to the topsoil via the incorporation and subsequent decomposition of tree litter. Hartemink *et al.* (1996), and Buresh and Tian (1997), detected subsoil nitrate levels in the order of 70 to 315 kg N ha^{-1} at 0.5- to 2 m depth in maize- based systems in Oxisols and Alfisols of Western Kenya.

They also found that sesbania fallows depleted this pool, thus capturi a resource that was unavailable to maize crops (Mekonnen *et al.*, 199' The source of this nitrate pool is believed to be the result of tl mineralization of organic N in the topsoil, which is relatively high these soils, followed by nitrate leaching into subsoil layers. The nitra anions are then held in the subsoil by positively charged clay surface

Subsoil nitrate accumulation and its depletion was detected in Ea Africa decades ago but such findings were not given practical attentic at that time. It is probable that trees also capture K at same depths similar soils and thus help prevent K deficiencies. In order for nitra anions to move, they must be accompanied by a cation; K is the ma leachable cation in such soils. Nitrate accumulation in the subsoil well documented in soils rich in Fe oxides that provide anion-exchang sites to hold nitrate ions (Cahn *et al.*, 1992). Many such subsoil however, are highly Al-toxic, preventing significant plant ro development, but subsoil acidity is not a widespread constraint in Africa soils cultivated by smallholder farmers.

The rotation of annual crops with short-duration fallows containir deep-rooted perennials holds promise as a way to use subsoil nitrat that would otherwise be unavailable to crops. This resource may not b replenished when cropping systems become more intense, as nitrat leaching from the topsoil may be diminished by more extensive cro root systems. The magnitude of the captured subsoil nitrate needs t be assessed in other soils, but soil chemistry indicates that subso nitrate accumulation will not be as significant in many other types soils found in Africa. Nevertheless there are 260 million ha of soils i Africa that have anion-exchange capacity in the subsoil. The use of thi hitherto unrecognized N source via its capture by deep-rooted trees i an exciting area of research in the region. Improved fallows wit leguminous species are a promising technology for improving maiz yields in nutrient depleted soils of East and Southern Africa. Studie report estimated 5000 farmers in Eastern Zambia and 10000 in Wester Kenya (Jama and Mafongoya, 1999) now adopting and adapting improve fallows for maize production. Whereas the improved fallows can mee the nitrogen needs for a maize grain yield of 3 to 4 t/ha, phosphoru needs must be met by application of inorganic P sources such as TSP c high quality rock phosphates (PR) like Minjingu PR.

In general planted fallows have potential in areas where:

- Land is not limiting
- Opportunity cost of labour is low
- Trees provide by-products such as fuelwood and fodder
- Soils of high pH and clay content
- Fallow species produce high quality biomass. On P deficient soils fertilization may be necessary to sustain the fallow effect o subsequent crops

Economic analysis of improved fallows was done using data from twelve farms in eastern Zambia (Table 3.4). Over a five year period, a hectare of improved fallows required 11% less labour than a hectare of unfertilized maize and 32% less labour than fertilized maize (Franzel *et al.*, 1999). The returns to the land Net Present Values (NPV) per hectare for fertilized maize were over 30% higher than for improved fallows. Assessing returns to labour, which is more relevant to most small holder farmers than returns to land because labour tends to be more scarce than land, improved fallows performed better than unfertilized and fertilized maize (Table 3.4). In this example, an increase in maize yields of only 1.1 t/ha was needed in the third year to cover the costs of establishing and maintaining the fallow relative to unfertilized maize in terms of returns to land and labour. The performance of improved fallows relative to continuous fertilized maize was too sensitive to changes in key economic factors. An increase in maize prices for example, raised the returns to fertilized maize at a much faster rate than the rise in the returns to improved fallows. Similarly, the relative profitability of the two practices was highly sensitive to price of fertilizer; where reductions in fertilizer price greatly increased the profitability of fertilized maize relative to improved fallows. Changes in the discount rate and in the labour and seedlings had little effect on the performance of improved fallows relative to fertilized maize.

Financial returns

Table 3.4. Comparison of two-year *Sesbania sesban* improved fallows and continuously cropped maize over a 5- year period, Eastern Zambia

Option	Returns to land: net present value (USD/ha)	Returns to labour: Net returns (USD) per workday
Continuous unfertilized maize	5	0.42
Improved 2 year-sesbania fallow	160	1.02
Continuous fertilized maize	203	0.93

Source: Franzel *et al* (1999)

There are, however, several concerns that need to be addressed. First, improved fallows may not be an option for a large number of farmers with very small land holdings. The biomass produced (and N recycled) by fallows could be constrained by low soil fertility and by pests. There are also uncertainties about Biological Nitrogen Fixation (BNF) – for instance, how much N is fixed relative to the needs of the crop and what should be the management practices of the fallow species that would enhance it (e.g., appropriate rhizobium for each species and the need for P application). Other issues of concern are N and water dynamics in fallow systems effect of improved fallows on soil physical properties and biological processes, effect of mixed fallow species on subsequent crops, how to prolong residual fallow effects on crops and P cycling in improved fallows. Unless these issues are addressed, short-duration improved fallows with leguminous species may not produce sufficient N for high maize yields especially when P is added and hybrid seed is used. This means the shortfall of N should be met through inorganic N fertilizers.

There is need to evaluate a wider range of improved fallow management options and understand their socio-economic limitations. Specifically, the following are areas of high priority:

a) economics of alternative improved fallow species (sesbania vs tephrosia),
b) coppicing fallows (gliricidia vs sesbania) and,
c) economics of pure (sole) fallows vs established intercropped with maize and other crops. There is need to assess impact achieved so far. This should include the following aspects: identifying the number and type of farmers adopting the technologies, the impact of adoption on food vs. cash crops and, the environmental effects on farm, household and village scales.

Finally there is need to understand the institutional support required to sustain a wide-scale adoption. Some of the key issues are the need to develop:

a) Community-based germplasm (seed) supply,
b) Individual nurseries and community nurseries,
c) Farmer researcher linkage groups,
d) Community fire control and grazing systems and,
e) Marketing and credit facilities.

Biomass transfer system

This technology may be practiced by any of the following ways:

a) Transfer of leaf biomass produced from one field to another on the farm

b) Transfer of biomass produced outside the farm
c) Recycling of nutrients through livestock manure
d) Movement of manure from pastoral areas to cropping fields

In Zimbabwe farmers traditionally collect leaf litter from miombo secondary forest as a source of nutrients to maize (Nyathi and Campbell, 1993). In the long term this practice is not sustainable for it mines nutrients from the forest ecosystems in order to build soil fertility in the croplands. Miombo litter collected is also of low quality and it may immobilize N instead of supplying N immediately to the maize crop (Mafongoya and Nair, 1997). An alternative means of producing high quality biomass is through establishment of on-farm biomass banks from which the biomass is cut and transferred to crop fields in different parts of the farm. In Western Kenya for example the use of *Tithonia diversifolia*, *Senna spectabilis*, *Sesbania sesban* and *Calliandra calothyrsus* planted as farm boundaries, woodlots and fodder banks or found along the roads as a source of nutrients has proven beneficial in improving maize production (Maroko *et al.*, 1998; Nziguheba *et al.*, 1998; Palm, 1995; Palm *et al.*, 2001). In a study by Gachengo (1996), tithonia green biomass grown outside a field and transferred into a field was found to be as effective in supplying N, P and K to maize as an equivalent amount of commercial NPK fertilizer, and in some cases maize yields were higher with tithonia biomass than commercial inorganic fertilizer. Recent work in Malawi (Ganunga *et al.*, 1998) and Zimbabwe (Jiri and Waddington, 1998) have similarly reported tithonia biomass to be an effective nutrient source for maize.

Biomass transfer using leguminous species is a far much sustainable means of maintaining nutrient balances in maize-based systems as these trees are able to fix atmospheric N_2. Tithonia is not a legume, and it does not biologically fix atmospheric N_2. The transfer of tithonia biomass to fields, therefore, constitutes the cycling of nutrients within the farm and landscape rather than a net input of nutrients to the system. The continual transfer of nutrients from tithonia hedges to crop fields constitutes nutrient mining and might not be sustainable for long periods. Whereas the application of fertilizers to tithonia could ensure sustained production of tithonia, this is unlikely to be an option for resource-poor farmers. The integration of tithonia with N_2-fixing legumes may merit investigation.

The issue of synchrony between nutrient release from tree litter and crop uptake can potentially be achieved in a biomass transfer system. The management factors that can be manipulated to achieve this are litter quality, rate of litter application, method and time of litter application (Mafongoya *et al.*, 1998; 1999). However variability in climatic factors such rainfall and temperature makes the concept

of synchrony an elusive goal to achieve in practical terms (Myers et al., 1994).

Although prunings from MPTs increased maize yield, cutting transporting and managing prunings on crop fields required high labour inputs (Jama et al, 1997; Jama et al, 1998; Mutuo et al., 2000). Where family labour is available at no additional cost, the technology can be profitable even where land is scarce (Jama et al., 1997; Mutuo et al., 2000). However, considering that farm labour is one of the most constraining input in smallholder agriculture, the associated cost makes this technology unattractive and may serve as a disincentive for its adoption by farmers. In monetary terms, the higher maize yield does not compensate for the high labour cost. In promoting this technology farmers may require to be provided with a source of additional resources to invest in labour and land. Most economic analyses have shown that it is unprofitable to invest in biomass transfer system when labour and land are scarce. However, in areas where land is abundant and the prunings are applied to high value crops like vegetables, the technology is profitable (ICRAF, 1997).

In summary, the biomass transfer system has greatest potential when biomass is of high quality and rapidly releases nutrients, the opportunity cost of labour is low, the value of the crop is high and if the biomass does not have other valued uses other than as source of nutrients

The effectiveness of biomass transfer as nutrient sources using organic inputs from MPT species depends on their chemical composition (Mafongoya and Nair, 1997). These systems can meet the N requirement of most crops in smallholder farming systems. However, they cannot meet the requirement of P. There is need to apply inorganic sources of P in addition to organic sources. When biomass is also valued as fodder there is need to assess the trade off of applying it directly to the soil or feeding it to livestock and then applying the resultant manure. There is evidence to indicate that depending on the quality of the biomass there may be no advantage in feeding it to livestock and then applying the manure as source of N to crops (Mafongoya et al, 1999). However, in other instances, it has been shown that it is more advantageous to first feed the biomass to livestock and then apply the resulting manure to crops (Jama et al., 1997). Among the areas that call for more research in the use of biomass transfer are the residual effects of low and high quality biomass, combinations of organic and inorganic nutrient sources, effect of biomass banks on nutrient mining and the economic analysis of the system.

Maize-Livestock Interaction and Zero Grazing Systems

Mixed crop-livestock farming systems are characteristics of large areas of Africa. There are ecological and socio-economic interaction between livestock and maize cropping systems whereby livestock provide manure, which is a source of nutrients to maize in many countries in subhumid Africa while the stover from maize is the source of feed to livestock during the dry season when there is shortage of high quality fodder. In addition, livestock serves as a form of capital to buy inorganic inputs for maize production and also as a means of transport to carry inputs and outputs from and to the markets.

Manure has traditionally been used as a source of nutrients before and after the advent of inorganic fertilizers. The use of manure can improve crop yields considerably. This has been shown in several studies and reviews (Ikombo, 1984; Probert *et al.*, 1995; Haque, 1993; Murwira *et al.*, 1995). The demonstrated benefits of manure include increase in soil pH, water holding capacity, hydraulic conductivity and infiltration rate and decreased bulk density. Manure can be an important source of nutrients, especially N, P and K. In Zimbabwe, for instance, estimates from the Mutoko communal area suggest that over 80% of the N applied to field and garden crops is derived from kraal manure and about 10% from leaf litter (Scoones and Toulmin, 1985). Details of manure management are presented in Part 7.

This section will concentrate on stall fed/ 'cut and carry' based dairy schemes which are important in the central highlands of Kenya, Chagga gardens of Kilimanjaro (Tanzania) and smallholder dairy schemes in Zimbabwe. In these systems farmers keep from one to five dairy cows or more depending on whether the farmer is practicing zero or limited grazing system. Generally, fodder is cut and carried to the animals confined in stalls. The main source of forage is napier grass (*Pennisetum purpureum*) which is normally grown in fodder banks and around the edges of the cultivated fields. Recently tree legumes like *Acacia angustissima*, *Calliandra calothyrsus* and herbaceous legumes like siratro have also been included in the fodder banks as cheap sources of protein. Additionally, crop residues are important source of supplementary feeds. This system offers potential to control quality of manure and losses of nutrients by:

- Type of feed used
- Management of manure
- Housing facilities of the animals
- Minimum volatilization losses of urine

In the longer term the recalcitrant component of the manure forms a reserve pool of mineralizable nutrients that will be available for plant uptake in future seasons. Manure has also the long-term effect of raising

soil organic matter levels with all the concomitant benefits associated with improved soil organic matter status of a soil. The quantities of manure available are, however, often inadequate to maintain soil fertility and crop yields. The quality is also often poor. This can, however, be improved through management practices (See Part 7).

Quantity and quality of manure available

Manure is generally a scarce commodity on most farms. The amount of manure available to a farmer is dependent on several factors such as herd size and management system (free grazing or zero-grazing 'stall fed', etc). For farmers with no livestock, the existence of manuring contracts whereby farmers can gain access to manure in exchange of crop residues is common in many places. Manure production is also dependent on seasonal differences and rainfall conditions, which determine availability of fodder. Manure production especially from unimproved livestock breeds in free-grazing, open systems is generally low and highly variable. Probert *et al.* (1995), estimated production levels of 1 ton/livestock unit/year for unimproved local production levels of local breed in maize-livestock system in the semi-arid parts of Eastern Kenya

In spite of the low levels of manure production, recommended manure application levels are often as high as 10 to 15 t ha^{-1} yr^{-1} (Grant, 1981), though the actual application rates by farmers are far much lower. The manure used in trials often emanates from feedlots and ranches with higher feed quality and supply than communal areas. The quality of kraal manure from livestock in communal areas is highly variable, with N levels as percentage of dry matter (DM) ranging from 0.46 to 1.98% (Tanner and Mugwira, 1984; Ikombo, 1984; Mugwira and Mukurumbira, 1985; Mureithi *et al.*, 1994). Such levels are far lower than N contents found in manures derived from feedlot cattle. The P concentration can vary greatly depending on the source, the diet of the animal, storage and management (Guar *et al.*, 1985). Additionally, communal area cattle manure contains high fractions of sand due to the mixing of manure with soil during trampling by the livestock (Mugwira, 1984). Nitrogen levels also vary between seasons with changes in the quality and availability of fodder resources.

One way to improve manure quality (i.e., nutrient content) is to supplement livestock with nutrient rich concentrates and fodder. Many trees and shrubs used in agroforestry systems provide fodder that can improve the quality of manure produced. Jama *et al.* (1997), showed that high P content manure (0.49% P) can be obtained if the grass fed to zero-grazed improved breed dairy cows is supplemented with the fresh leaves of *Calliandra calothrysus*, a leguminous shrub with fodder value. The effects of the resultant high quality manure, either broadcast-applied and soil-incorporated or spot-placed in the planting hole at the rate of 2

$t ha^{-1}$ (equivalent to 10 kg $P ha^{-1}$) compared to inorganic P fertilizer (triple superphosphate, TSP) applied at the same rate on maize yield at two P deficient sites in Western Kenya was that maize yield increased by 3 to 4 times over continuous maize cropping in the first season after application as well as during the second season when residual effects were monitored. Net economic benefits were, however, higher for manure (no difference between broadcast-applied and spot-placed) compared to TSP, (Jama, 1999). Thus, the relatively high net benefits for manure application whether placed with the seed or broadcast, highlights the need for high quality manure as a source of nutrients on P deficient soils.

While better management of the available manures may improve their quality, the amounts available may still pose constraints in smallholder farms. On these farms, it is important to examine ways to increase the use efficiency of the little available manure. One such strategy is placement of the manure in the planting hole instead of broadcasting it. This is a common practice among farmers as a measure to maximize the use of a limited resource, reducing leaching and volatilization effects and maximizing yield. Spot placement requires farmer knowledge, skills and labor inputs. To aid this or any other strategy that aims at efficient use of manure, information on the rates of decomposition and mineralization of the manure is required.

Nutrient losses from manure

Given the importance of manure in maintaining productivity of the soil, Ransom *et al.* (1995), concluded that sustained production of fodder and developing improved manure handling techniques that minimize nutrient losses are essential elements in sustaining maize productivity in maize-livestock-based systems. Data on losses of nutrients during manure management in smallholder farming is generally lacking. Some recent estimates, however, suggest that up to 60% N and 10% of P can be lost through poor manure management (Shepherd *et al.*, 1996). Although there are uncertainties in these estimates, they do suggest the need for accurate measurement particularly in the context of intensive dairy schemes with high manure fluxes and the need to device appropriate management practices that minimize losses.

Since 40 to 60% of the N excreted by livestock (ruminants) is in the form of urine, the potential for nutrient loss can be greater under stall-feeding than range grazing extensive systems where only excreta is captured and applied to crop fields (Powell and Williams, 1995). More intensive stall-feeding systems of livestock could, therefore, increase nutrient losses and jeopardize long-term soil productivity if technologies are not available that capture and recycle the nutrient voided by stationary animals.

In systems involving livestock, nutrients can be lost via severa avenues. An important one in traditional livestock enclosures ("bomas' is the leaching and loss of nutrients from the surface soil, for example Probert *et al.* (1995) from their studies in Western Kenya observed tha the enrichment of N and K extended to the full sampling depth of 2.1m but for P the effect was restricted to the surface layers as expected fror its low mobility. This leaching of nutrients from 'poor' storage shows a accumulation of nutrients beneath the 'bomas', which act as sinks fc nutrients that have been removed from farm soils or crop lands and ar no longer being put to use. Current studies in Zimbabwe have bee designed to reduce nutrient losses from manure through constructio of better kraals (Nzuma and Murwira, 1998).

The rate of mineralization of N is faster, and losses from volatilizatio are greater from animal excreta than from plant litter. This make ammonia volatilization a major loss pathway of N from manure. Fc instance, Vertregt and Rutgers (1988), estimated that ammonia losse accounted for four times as much of the N excreted from animal compared with N losses from decaying herbage from pasture. Hence although animal excreta provide nutrients for plants in a more usabl form, the loss of N from the system could be much higher. The loss ca however be reduced by incorporating manure into soil at time of planting controlling losses in the kraals by use of residue as bedding as well a proper citation of the kraals (Murwira, 1995).

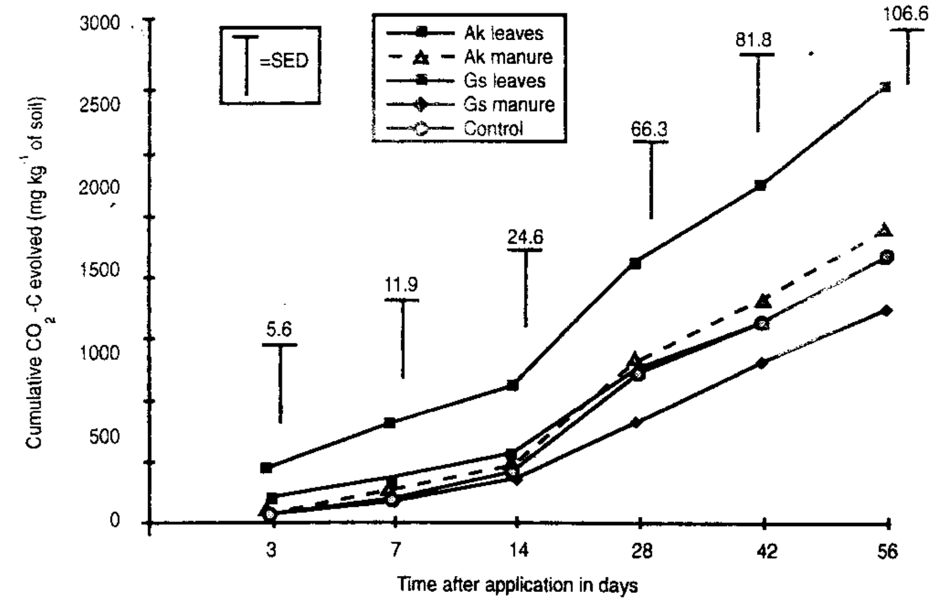
Decomposition and N release patterns of leaves and manure

Decomposition and nutrient release rates (especially N) are determine by the quality of leaves or manures, the environment and decompose organism present (Swift, 1987). The quality of organic inputs als determines the type of SOM fractions formed after application of organi inputs. Quality here refers to the constituents (chemical compositior and the nutrient contents of the organic input (Palm, 1995; Mafongoy *et al.*, 1997; Cadisch and Giller, 1997). Organics of high quality ar high in N but low in both lignin and polyphenol content. Such hig quality organic resources decompose and release N rapidly. On the othe hand, low quality organics are low in N but high in polyphenol an lignin contents. Low quality organic materials decompose slowly an may immobilize N and other nutrients.

Numerous examples in literature indicate that quality of an organi input is an important aspect in determining the rate of decompositio and mineralization of that particular organic once incorporated into th soil. For example, Figure 3.2 gives the results of a study conducted i Zimbabwe to compare the rates of decomposition of acacia and gliricidi leaves compared to the manures that resulted from feeding livestoc (goats) with those respective leaves. *Gliricidia* leaves decomposed an significantly evolved more carbon dioxide than the rest of the organi

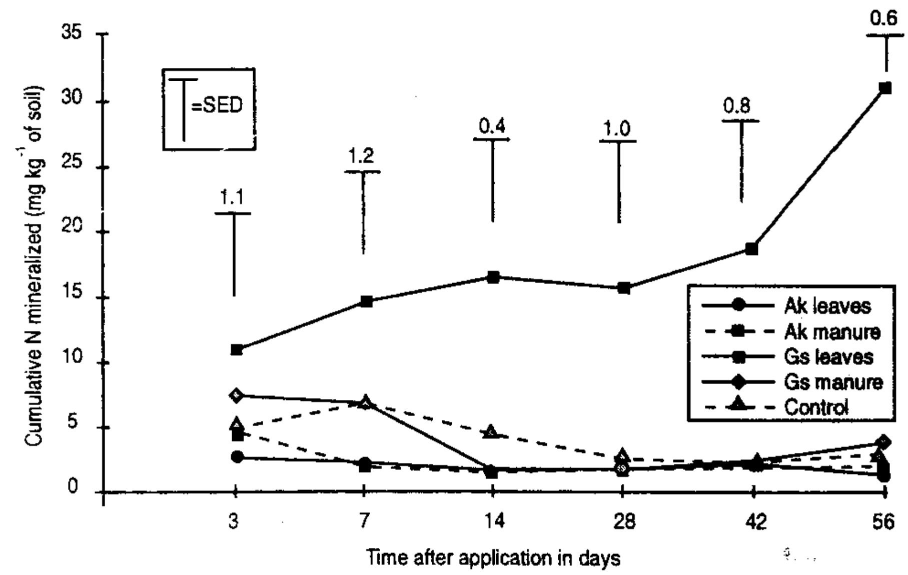
amendment. There were no significant differences in decomposition patterns of *Acacia karoo* leaves, *Acacia karoo* manure and *Gliricidia sepium* manure. Cummulative N release also followed the same pattern (Figure 3.3) (Mafongoya *et al.*, 1999).

Figure 3.2. Cummulative amount of CO_2 evolved as affected by tree leaves, manure and incubation period (AK = Acacia kroo; GS = Gliricidia sepium)



Source: Mafogoya *et al* (1999)

Figure 3.3. Cummulative amount of net N mineralized as affected by tree leaves, manure and incubation period (AK = Acacia kroo; GS = Gliricidia sepium)



Source: Mafogoya *et al* (1999)

Nutrient cycling in a mixed farming system can be manipulated through the chemical composition of the diet and manure quality. Whether to feed leaves to livestock and then apply the resulting manure to crops or to apply the prunings directly to crops depends on crop response to mulching, animal response to feed suppliments and the prices of the crop and animal products. For example, recent work by Jama *et al.* (1997) from Eestern Kenya has indicated that leguminous tree species such as *calliandra* are best profitable when utilized as fodder supplements for livestock as compared to direct application to crops as green manure. The economics of these options needs further evaluation on farmer's fields.

Improving quality of manure through composting with rock phosphate materials

Rock phosphate materials are quite an abundant resource in East and Southern Africa (Buresh *et al.*, 1997). These could be low cost fertilizer materials. Their chemical composition and reactivity limit the use of these rock phosphate materials. Dorowa Phosphate Rock (DPR) which is the main mineral source of P in Zimbabwe provides an opportunity to develop low cost P fertilizer. The direct use of DPR as a P fertilizer has been reported to be agronomically ineffective both in greenhouse and field studies (Dhliwayo and Mukurumbira, 1996).

Benefication (removal of impurities) of DPR is needed to enhance its agronomic effectiveness. Studies in Zimbabwe on composting DPR with cattle manure have shown higher residual effect of composted DPR compared to inorganic P fertilizers alone (Dhliwayo, 1998). The percentage of groundnut yield over control was 74% and 99% for manure and manure and DPR composted in the kraal (Table 3.5). These studies have shown that residual agronomic effectiveness of DPR and cattle manure can be greatly enhanced by composting DPR with cattle manure in kraals. This technology is feasible to farmers who stay near DPR deposits with minimum transport costs.

Table 3.5. Effect of landuse on maize grain yields kg/ha

Land use systems	Season: Long rains 96		Short rains 96		Long rains 97	
Fallow system	No P	P	No P	P	No P	P
Natural fallow	1452	2180	1286	1501	1863	2813
Continuous maize	595	774	810	849	1432	1517
Sesbania fallow	2112	2630	1393	1246	2336	2183
Sesbania fallow (seedlings)	2289	2865	1512	1706	2365	2395
SED	256		166		313	

Source: ICRAF (1997)

In East Africa the most promising PR sources are Minjingu in northern Tanzania and Busumbu in Eastern Uganda. Minjingu PR has been reported to be a very suitable source of P to crops in P-deficient soils because of its high solubility and its high relative agronomic effectiveness (Bromfield *et al.*, 1981; Woomer *et al.*, 1997). On the other hand, Busumbu PR is of generally low solubility and lesser reactivity compared to Minjingu PR. However, an option of blending Busumbu PR with small quantities of triple superphosphate (TSP) and/or manures to improve its reactivity is currently being tested in Western Kenya (Jama *et al.* 1999).

Strategies for Integrated Nutrient Management

The primary goal of integrated nutrient management (INM) is to combine old and new methods of nutrient management into ecologically sound and economically viable farming systems that utilize available organic and inorganic sources of nutrients in a judicious and efficient way (Franzluebbers *et al.*, 1998). INM attempts to achieve tight nutrient cycling with synchrony between nutrient demand by crop and release in the soil while minimizing losses through leaching, runoff, volatilization and immobilization. Organic nutrient sources include plant residue, leguminous cover crops, mulches, green manure, and household wastes. Judicious combination of these organic resources with inorganic fertilizers can help ensure immediate nutrient release for present crop as well as the long-term build up of soils nutrient reserves.

In the recent past a number of strategies for soil organic matter management have been studied. These include:

(a) Returning of organic materials to the soil to replenish soil organic carbon lost through decomposition (recycling of plant and animal residues, farmyard and green manuring, composting, cover crop rotation);

(b) Ensuring minimum disturbance of the soil surface (residue mulch, conservation tillage) to reduce rate of decomposition;

(c) Reducing soil temperature and water evaporation by mulching the soil surface with plant residues; and

(d) Integration of multipurpose trees and perennials into cropping systems to increase production of organic materials (Franzluebbers *et al.*, 1998). Most of these strategies have been discussed in the earlier sections of this chapter and point to the realization that judicious use of both organic and inorganic nutrient management strategies could be a solution to the declining soil fertility problem in the maize-based systems of East and Southern Africa.

Many farmers in Africa use organic or inorganic inputs or a combination of organic and inorganic sources of nutrients to try to meet crop demands. This is necessitated by inadequate amounts of each input.

Crop yields obtained may be low because of inadequate amounts added, low quality organic materials and inappropriate and inefficient combinations. Given the problems of inorganic fertilizer procurement in Africa, the objective should be to provide much of the nutrients through organic inputs especially N and making up the shortfall for P and N through inorganic fertilizers.

Results of Itimu *et al.* (personal communication) showed that the interaction between mineral N and organic residues indicated that there was no bonus to be gained in terms of increasing fertilizer use efficiency by mixing mineral and organic inputs at moderate levels. Significant effects on soil structure, nutrient retention and root penetration is likely to be increased only when sufficient organic inputs have been added compared to use of mineral fertilizers (Palm *et al.*, 1997). However, there are exciting results of increasing phosphorus availability by mixing inorganic P sources with high quality residues such as tithonia. This area deserves further research.

To make recommendations for combined nutrient use, information on the fertilizer equivalency of organics is needed. Lacking is the understanding of how much of the different quality organics to apply to get yields equivalent to those obtained from inorganic fertilizers and how much of the applied nutrients remain to be used by the subsequent crops. Recent research has shown that low quality organic inputs have longer residual effects than high quality organic inputs (Snapp *et al.*, 1998). However, the long-term effects of low quality organic inputs on soil physical and chemical properties need further research. Guidelines are therefore needed which link the use of mixtures and organic inputs of different quality and their short-term fertilizer equivalency value and also their longer-term residual effects on SOM pools. These guidelines can only be obtained from well-designed long-term experiments conducted in soils with appropriate limiting nutrients. Farmer's circumstances, perceptions including available resources allocation, soil types and socio-economic circumstances need to be included in such experiments.

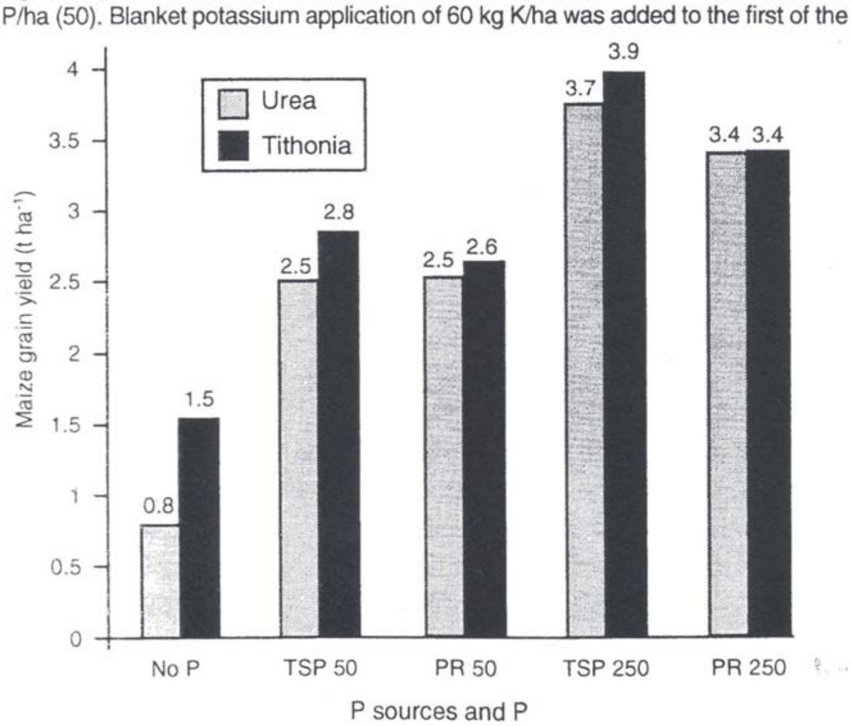
The following section highlights a few examples on integrated nutrient management and especially on the need for phosphorus provision that can not be supplied in sufficient quantities by organic sources to meet crop demands.

Use of tithonia and inorganic phosphorus fertilizer

Most soils of Western Kenya and some parts of Southern Africa are deficient in phosphorus, nitrogen or both nutrients. Work on soil fertility recapitalization (ICRAF, 1996) has shown interesting results with the use of organic and inorganic nutrient sources. The work compared leafy biomass of tithonia (*Tithonia diversifolia*) and urea as sources of N and two sources of P fertilizer (Phosphate rock- PR and triple superphosphate-TSP). Application of P either as PR or TSP significantly increased maize

yields with tithonia and urea application (Figure 3.4). There was a significant yield increase when tithonia was added to the P fertilizer in comparison with commercial N fertilizer. Maize grain yields were higher after application of tithonia than they were after urea in the absence of added P and with each P source (Figure 3.4). Further observations of the same data revealed that both tithonia and TSP at equal P application rates rapidly increased plant available P in the soil as determined by resin P extraction. The increase was however, more with tithonia than with TSP indicating that tithonia was more effective than TSP in reducing P sorption (fixation) by iron and aluminium oxides in the soil (Jama, 1999; unpublished). It has been suggested that, unlike inorganic TSP, tithonia reduces P sorption by producing organic acids during decomposition that compete with P for soil sorption sites (Nziguheba *et al.*, 1998). The integrated use of tithonia with commercial inorganic P fertilizer also resulted in greater soil biological activity as determined by higher microbial biomass P than either sole tithonia or sole TSP treatments (Jama, 1999; unpublished). The effectiveness of fresh tithonia leafy biomass for soil fertility improvement can be partially attributed to the fact that tithonia is a high quality biomass that rapidly decomposes releasing plant available nutrients like P, N and K.

Figure 3.4. Maize responses to phosphorus and tithonia applications in Western Kenya representing annual maize yield from the two maize cropping seasons averaged over three sites. The green foliar biomass of *Tithonia diversifolia* was incorporated into the soil at the beginning of the long-rains at the rate of 1.8 t dry matter ha to provide 60 kg N/ha, 6 kg P/ha and 60 kg K/ha. Triple superphosphate (TSP) and Minjingu phosphate rock (PR) were added at a recapitalization rate of 250 kg P/ha (250) or annually at 50 kg P/ha (50). Blanket potassium application of 60 kg K/ha was added to the first of the two crops.



Source: Bashir Jama (unpublished)

Use of sesbania fallows and phosphorus fertilizer

Improved fallows with leguminous trees such as *Sesbania sesban* have been shown to overcome N deficiency in maize through biological nitrogen fixation and the deep capture of subsoil nitrate. Many studies have shown that trees cannot supply enough P through their biomass or increase the availability of P pools in the soils.

Once N deficiency has been overcome through use of improved fallows, there is need to ensure adequate supply of P to crops in order to avoid P negative balances. Work of ICRAF (1997), in Western Kenya has shown promising results with sesbania fallows and the use of inorganic P fertilizers such as TSP. Sesbania fallow plots were split into two plots; one half received 22 kg of Pha^{-1} as TSP and other half received no fertilizer. The application of P increased the yield of maize in all systems but most in the plots that were under sesbania fallows (Table 3.6). Economic analysis showed that higher returns to labour and land were obtained from sesbania fallow system with P compared to the other land uses. The conclusions from these studies have shown that in order to take full benefits of the fallows, inorganic P has to be applied at a moderate rate of 20-kg P/ha. Recurrent P application at this rate are necessary if economic benefits are to be sustained. The results of this study are from one location only. There is need therefore to test these results in more sites in East and Southern Africa to determine the need for inorganic P in improved fallows.

Table 3.6. Residual effect of composted rock phosphate, manure and inorganic fertilizers on groundnut grain yield and stover yield (kg/ha)

Fertilizer treatment	Kernel yield	Stover yield
Control (no fertilizer added)	915	2626
Manure + DPR composted in kraal	1823	5671
Single superphosphate fertilizer	1271	3476
Compound D fertilizer	1253	3517
LSD (P<0.05)	317	792

Source: Dhliwayo, 1998

Integration of manure with inorganic fertilizers

In systems where manure is a major avenue for recycling nutrients, an important consideration is whether manure alone can meet and sustain the nutrient needs for a reasonable crop yield. There is sufficient evidence to indicate that the nitrogen demand (and to some extent K) to produce a reasonable maize yield crop can be met by manure. Phosphorus, however, cannot be provided in sufficient quantities by manure (Palm *et al.*, 1997) therefore an important issue in this regard is improving both the P content and P cycling potential of manure.

Probert *et al.* (1995) in a review of the African literature reported a range of P concentration of manures from 0.06 to 0.57%. The P concentration can vary greatly depending on the source, the diet of the animal, storage and management (Guar *et al.*, 1984). In nutrient-flux studies conducted in the maize-livestock-coffee system studies, Ransom *et al.* (1995), observed that with the exception of phosphorus, inputs of nutrients through manure far exceeded their removal by stover. Application of inorganic P supplied more than 50% of the phosphorus needs. Therefore, in order to meet the P requirements for a reasonable crop of maize, inorganic P must be integrated with manures.

Besides P, manure alone is also unlikely to meet the N requirements of high yielding maize crops because of its inability to supply continuously large amounts of readily available N (Mugwira, 1985). Integration of manure and inorganic fertilizers may result in greater residual effects of the organic than the inorganic sources and also the added advantages of manure (in addition to supplying nutrients), such as improved soil physical properties (Murwira *et al.*, 1995).

Case Studies

Hedgerow Intercropping in the Central Highlands of Kenya

A hedgerow intercropping experiment was initiated in 1992 in the subhumid tropical highlands of Central Kenya to address the constraint of declining soil fertility caused by continuous cropping without addition of adequate fertilizers and/or manure inputs (Mugendi *et al.*, 1999a, b). The overall objective of the trial was to evaluate the influence of soil-incorporated leafy biomass of *Calliandra calothyrsus* and *Leucaena leucocephala* on soil fertility improvement and crop sustainability.

Results from this study showed (Fig. 3.7) that maize alley-cropped with *leucaena* and with prunings incorporated into the soil produced higher grain yield than non alley-cropped, no fertilizer control (absolute control). The yields were also higher compared to those obtained from the treatment that received the recommended level of N fertilizer (50 kg Nha^{-1}). On the other hand, calliandra alley-cropped treatments produced yields equal to or less than those that absolute control did (Mugendi *et al.*, 1999a; b).

The choice of the multipurpose tree or shrub selected for hedgerow intercropping purpose, is very crucial for some tree species tend to be more competitive than others, drastically reducing the benefits of alley cropping due to competition between the hedgerow tree species and the companion crop for growth resources. For example, results from the above-mentioned study showed that *Calliandra* hedges were more competitive than *leucaena* hedges. The yields of *Calliandra* alley-cropped maize were, on average, 50% lower than those of non alley-cropped

treatments that received *Calliandra* prunings from *ex situ* grown trees (biomass transfer), whereas the decrease was, only 8% when the similar *Leucaena* treatments were compared. It was, however, noted that, both *Calliandra* and *Leucaena* treatments that received *ex situ* prunings produced yields that were not significantly different from each other in all the seasons (Mugendi *et al.*, 1999a;b). The competitiveness of *Calliandra* over *Leucaena* hedges was further affirmed by analyzing the yield data through the approach (equation) developed by Ong (1996) where the effects of including or excluding hedges or prunings were assessed in relation to the performance of the absolute control. A simplified version of the equation expresses the overall tree-crop interaction (I) as a function of soil fertility (F) and tree crop competition (C), ie,

$$I = F + C$$

Where

I is the overall tree-crop interaction (measured by the difference between crop yields of the alley cropped, prunings applied treatments (Hm) and the absolute control where no prunings were applied (Co)),

F is the benefit of tree prunings on soil fertility (estimated by the yield difference between *ex situ* applied prunings treatments (Cm) and the control (Co)), and

C is the crop yield reduction due to interspecific competition between tree and crop (measured from the yield difference between Cm and Hm).

Table 3.7. Interaction, fertility, and competition effects of Calliandra and Leucaena hedges on maize yield (Mg/ha) in the subhumid tropical highlands of Kenya.

Season	Treatment	I (Hm-Co)	F (Cm-Co)	C (Cm-Hm)
SR 94	*Calliandra c.*	0.15	0.53*	-0.39
	Leucaena l.	0.78**	0.31	0.47*
LR 95	*Calliandra c.*	-0.62*	0.01	-0.60*
	Leucaena l.	0.46*	0.56*	-0.1
SR 95	*Calliandra c.*	-1.03**	1.46***	-2.50***
	Leucaena l.	0.44*	1.24**	-0.80**
LR 96	*Calliandra c.*	0.18	1.38***	-1.30***
	Leucaena l.	1.80***	2.08***	-0.28

Level of significance: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Seasons; LR = long rain; SR = short rain
I = interaction, F = fertility, and C = competition;
Hm = alley crop, prunings applied, Co = monocrop, no fertilizer (absolute control), and Cm = monocrop, prunings applied.

It is evident from this table that there was a significant negative interaction (I) between calliandra hedges and maize yield in two of the seasons (LR and SR 1995) whereas the interaction was positive (but not significant) in the remaining two seasons. On the other hand, leucaena hedges had a positive significant interaction with maize yield in all the seasons. It is further observed that fertility factor (F) for both species was almost identical across the seasons, but competition (C) for calliandra was much higher than leucaena's resulting in the observed negative interactions for calliandra hedges with maize yield.

The competitiveness of calliandra tree hedges over leucaena's could be explained by the root morphology of the two species. Calliandra trees develop strong superficial root system in addition to the tap root whereas leucaena is reported to have a strong tap root system that develops few lateral roots which also grow downward following emergence with later root development tending to be confined in the lower levels of the soil (van Noordwijk *et al.*, 1996). Results on the total root length (unpublished data) indicated that 60% of all the calliandra roots were located in the top 90 cm (soil) while only 25% of leucaena roots were found in the same soil depth. Thus, calliandra roots that occupied 60% of the top 90 cm depth competed more intensely with maize crop compared to leucaena whose greater percentage of roots were located below the effective rooting zone of the maize crop. Indeed, Jama *et al.* (1998) demonstrated that calliandra had the greatest root density in the top 15 cm of soil when compared to four other multipurpose tree species (*Eucalyptus grandis, Sesbania sesban, Markhamia lutea*, and *Grevillea robusta*) evaluated in the Western highlands of Kenya.

The importance of choosing appropriate tree species for alley cropping under different environmental conditions was further emphasized by Jama *et al.* (1995), who observed that, in the semiarid or subhumid conditions of Kenya, maize grain yield was better when alley-cropped with *Senna (Cassia) siamea* than with leucaena.

Results from moisture-stressed conditions suggest that alley cropping technology may not be effective in these conditions (Rao *et al.*, 1990; Jama *et al.*, 1995). Low biomass production of the hedgerow tree species and severe competition (that exceeds the fertility factor) for water are the major drawbacks limiting the potential of prunings to improve fertility and productivity of soils in these regions (Sanchez, 1995). In such cases, a biomass transfer system (cut-and-carry system or *ex situ* grown biomass) might be more beneficial than alley cropping system (Jama *et al.* 1995).

Despite the promising results shown by the alley cropping technology in the humid and subhumid regions of the tropics, the question of labor availability needs to be addressed properly before a wide adoption by farmers can be envisaged. The technology is labor-intensive with much of the demand for labor occurring during the rainy season, which

happens to be the busiest time of the year (Nair, 1993). Additional lab(for persons already fully occupied at peak labor seasons is considere more costly than when additional demands come during slack period: The cost of production will therefore be increased considerably additional labor must be hired (Hoekstra, 1987). Although thes additional labor costs will be offset by increased yields, the immediat need for additional labor could sometimes be a disincentive to th adoption of the technology (Kang *et al.*, 1990).

Rebuilding the Productive Capital of African Soils by us of Phosphate Rock (P Recapitalization)

Soil fertility depletion in smallholder farms is the major biophysic root cause for the declining per-capita food production in most of sub Saharan Africa (Sanchez *et al.*, 1997). This is attributed to input (nutrients not exceeding losses, especially with harvested products. On such area is Western Kenya where phosphorus losses of 3-13 kg ha^{-1}y over several decades have led to maize yields of less than 1 tha^{-1} (Sanche *et al.*, 1997). Meanwhile, population growth coupled with reduction i farm sizes has resulted in less land available for food production. Thes pose a serious threat to food security throughout the Eastern an Southern Africa.

Although P deficiency is widespread in East Africa, it is most sever in the densely populated highlands of Western Kenya. Responses (maize to P are significant even at rates as low as 10 kg Pha^{-1} (Jama (*al.*, 1997) indicating the importance of adding P to crops in this area. survey in three districts of this region, for example, indicated that abou 80% of the smallholder land used for maize production is deficient i available soil P.

Options for P inputs are organic materials, mineral P fertilizers (phosphate rocks (PR). Phosphorus content of organic materials (e.g leaves of trees and shrubs, farmyard manure) are generally low to provic enough P for annual crops (Palm *et al.*, 1997). Manure is the mos common soil amendment in Western Kenya, but the majority of th farmers in the area own no livestock and therefore have no source (manure (Shepherd and Soule, 1998). Thus low P content, low availabilit and competing uses and labor will generally preclude exclusive use (organics for P fertilization requirements, although they are certainl important as supplements.

There are PR deposits in East Africa, which have a proven capacit to alleviate phosphorus deficiency. The prevailing soil conditions ar also attractive to the use of PR. The direct use of PR generally require acidic soils with pH less than 5.5 (Sanchez, 1976; Rajan *et al.*, 1996 This is the case for most soils in Western Kenya.

Phosphate rock use

The use of indigenous PR has recently received tremendous interest as an alternative to mineral P fertilizers that are nearly all imported, high priced and often unavailable when needed. There are a number of PR deposits of variable reactivity in East Africa that differ greatly in their P composition and suitability as sources of P for P-deficient soils such as those in Western Kenya (Van Straaten, 1997). According to a recent report by Van Straaten (1997), the most promising PR sources are Minjingu in Northern Tanzania and Busumbu in Eastern Uganda.

A number of studies have highlighted the suitability of Minjingu PR as P source for crops in P-deficient soils. For instance, Bromfield *et al.* (1981) reported a relative agronomic effectiveness (RAE) of 75% for Minjingu PR in the five seasons following application to maize in Western Kenya. Based on results of 559 comparisons of rock and fertilizer at equal levels of added P, Woomer *et al.* (1997) also observed higher maize yield increases with Minjingu than with some other PR found in Africa. They concluded that strong potentials exist to further develop the Minjingu PR.

With the exception of Minjingu (biogenic sedimentary), most of the other PR deposits of Eastern and Southern Africa are weathered carbonatite deposits of igneous origin and of generally low solubility, and often with substantial Fe and Al oxide content. Typical of such deposits is Busumbu PR in Eastern Uganda. Busumbu PR is of lesser reactivity than Minjingu but close proximity to Western Kenya (less than 10 km away) compared with Minjingu that (greater than 820 km away) makes it attractive. There are known natural PR deposits in Kenya (e.g., Rangwe valley and Mrima hills) but they are not as reactive as either Minjingu or Busumbu PR.

The choice between soluble P fertilizers and PR as a source of P for crops depends on relative agronomic effectiveness (RAE) and cost. Relative agronomic effectiveness is defined as yield increase with PR relative to that with TSP expressed as a percentage. For correct determination of RAE, P should be the only nutrient limiting crop yield.

Phosphate rocks with low reactivity can be processed in different ways to improve RAE. One method is the compaction of PR with water-soluble P fertilizer, such as TSP. This is, however, likely to be costly on large-scale operation. The impurities, particularly magnetite, can also be removed through magnetic separation using inexpensive small-scale operations. These produce a concentrate of 13% P which can then be blended with mineral fertilizers (e.g., TSP) to increase its reactivity. Through the hydrolysis of TSP, the blend provides an initial quick dose of P and a sustained slow release of P as the acid produced by the hydrolysis process slowly reacts with the PR. Busumbu PR concentrate and a blend made from it (70% Busumbu: 30% TSP) are currently being tested in researcher-managed field trials in Western Kenya.

Studies with phosphate rock in Western Kenya

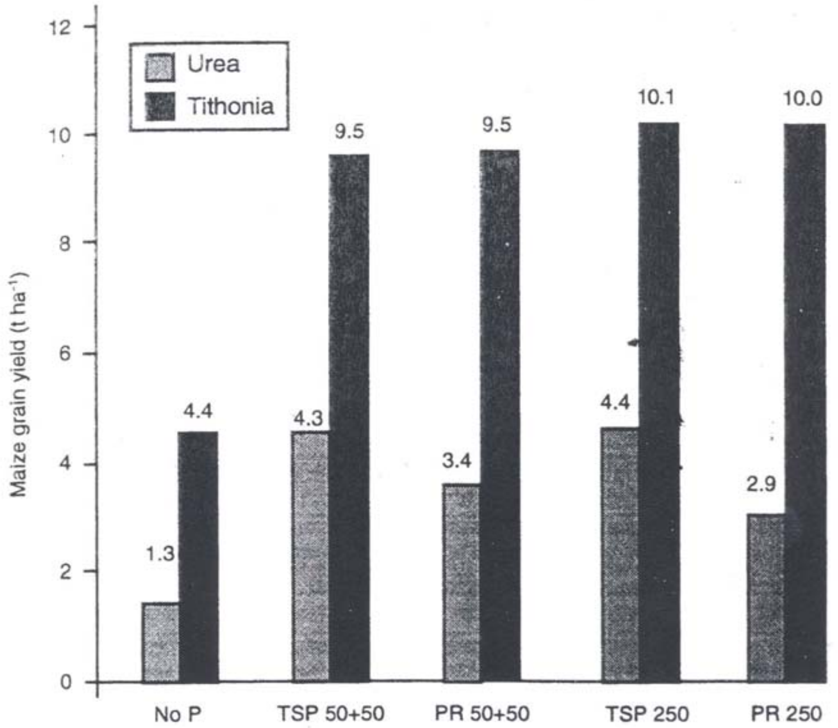
The International Centre for Research in Agroforestry (ICRAF), in collaboration with Kenya Agricultural Research Institute (KARI), Kenya Forestry Research Institute (KEFRI) and Tropical Soil Biology and Fertility (TSBF) Programme, began work with Minjingu PR in Western Kenya in 1996. The first study compared Minjingu PR with TSP at annual applications of 50 kg P/ha and a large one-time application of 250 kg P/ha, both broadcast-applied and soil-incorporated. Potassium was blanket applied to all treatments at 60 kg/ha. Nitrogen was applied annually at the rate of 60 kg/ha through either urea or foliar biomass of *Tithonia diversifolia*, a shrub common in hedges and roadsides in Western Kenya. The N rate of 60 kg ha is the recommended rate for maize in area. Maize yield responses to N application beyond this rate are usually small, probably because of the inherently high organic matter (3.0 to 3.3%) of the soils in many areas. Rapid mineralization of soil organic matter under the humid and hot conditions of the area can often supply N sufficient for at least 1.0 t dry matter ha maize grain yield.

Tithonia foliage has high concentrations of N, P and K and decomposes very rapidly in the soil (Jama *et al.*, 2000). The study was conducted at three sites where the soils are classified as Kandiudalfic Eutrudox (Soil Taxonomy) or Ferralsol (FAO-UNESCO 1979), pH 5.1 with clay content of 30 to 35%. These sites are fairly representative of the soils and rainfall conditions of the Western Kenya highlands neighboring Lake Victoria.

The annual maize yield from the two maize cropping seasons in the first year, averaged over three sites, indicated comparable response for the two P sources. Maize yield increased dramatically with the application of P at either 50 or 250 kg/ha (Fig. 3.5). Without P but urea as N source, maize grain yield averaged 0.8 t/ha. Maize grain yields less than 1.0 t/ha is typical in this area, which has highly P deficient soils (Sanchez *et al.*, 1997). Such low yields are not sufficient to feed the large number of people in the area. As a consequence, there has been considerable migration of people to cities and farms elsewhere to seek off- farm employment that can supplement their food and other needs.

It is interesting to note from Fig. 3.5 that with no P added, maize yield was higher with tithonia alone (1.5 tha^{-1}) than urea alone (0.8 tha^{-1}). This was probably due to the P (6 $kgha^{-1}$) supplied by tithonia applied at the rate sufficient to provide 60 $kgha^{-1}$. Responses of maize to P are known to be significant in this area even at rates as low as 10 kg P/ha (Jama *et al.*, 1997). The addition of P at 50 $kgha^{-1}$ (either as TSP or PR) increased maize grain yields by at least three times (2.5 tha^{-1}) compared to yields from urea alone (no P applied) and by about two times with tithonia alone. As expected, the yields were higher with application of P at the rate of 250 $kgha^{-1}$, with the increases being about four to five times those with urea alone.

Figure 3.5. P Sources and P Rates



Source: Bashir Jama (unpublished)

The RAE of Minjingu PR from this study averaged 83% with tithonia and 93% with urea as N source. In another multi-location study, RAE of Minjingu PR averaged only 70% in the first year in 26 P responsive sites in Western Kenya (Lijzenga, 1998). Bromfield *et al.* (1981) also reported a RAE of 75% for Minjingu PR in the five seasons following application to maize in Western Kenya. In an on-going, long-term trial with maize on an acid, P-deficient soil in Western Kenya, the RAE in the first season after P application averaged 74% at 50 kg P/ha and 80% at 250 kg P/ha (ICRAF, 1997). These high RAE would suggest that Minjingu PR could be used as a substitute for TSP.

Besides the supply of nutrients, organic inputs may also enhance PR solubility. Direct enhancement of Minjingu PR solubility was demonstrated by Ikerra *et al.* (1994), with compost- and manure-amended soil in Tanzania. Such an effect would, indeed, be desirable for low soluble Busumbu PR. No data are available yet on the RAE of Busumbu concentrate (BP) and BP-TSP blend in Western Kenya. Observations from ongoing field trials, however, suggest that a blend of 70% BP and 30% TSP might be comparable to Minjingu PR in RAE, whereas BP alone is less effective.

Economics of phosphate rock use

Minjingu PR is the only deposit in Eastern Africa with sufficient quantity and reactivity hence potential for direct application. Although far from Western Kenya (820 km away), the use of Minjingu PR is likely to be more economical than TSP in Western Kenya. The estimated retail price at Maseno in Western Kenya in December 1996 ranged from US$ 1.3 to 1.8 kg/P compared with about US$2.36 kg P^{-1} of TSP (Buresh *et al.*, 1997). Minjingu PR on a unit P basis was, therefore, 55 to 76% of the cost of TSP. This estimate should, however, be interpreted with caution as it was based on limited amount of PR acquired for on-farm research by farmers in a pilot project. It could become even cheaper if the PR was mined and delivered to Western Kenya on a large scale.

The economics works out favorably for Minjingu PR with its estimated 55 to 76% relative cost compared with TSP and approximately 70 to 75% RAE on acid soils in Western Kenya. The one-time large application of 250 kg/ha is perceived as a corrective measure for severely P-deficient soils as opposed to a gradual build-up of phosphorus capital through annual applications of small amounts. However, logistic costs, credit schemes and soil properties will be the main factors involved in the choice of P rates to use.

Benefits of integrating inorganic P sources with organic fertilizers

Based on the encouraging agronomic results and costs of Minjingu PR in Western Kenya, a pilot project was initiated in 1997 with the objective of disseminating to farmers the integrated technology of Minjingu PR application and organic sources of nutrient. This combination was effective in sites with multiple nutrient deficiencies as the organics primarily overcame N and K deficiencies while the PR met the P needs. Because of their low tissue P concentration, the organics cannot meet the P requirements of the crops unless applied at high rates, which is unfeasible and uneconomical.

The major organic sources of nutrients available to farmers were:

(1) tithonia leaf biomass from hedges on farms and
(2) short-duration improved fallows with fast-growing species such as *Sesbania sesban*, *Crotolaria grahamiana* and *Tephrosia vogelii*.

Tithonia is targeted mainly for biomass transfer while the other woody perennials are for improved fallows. These species are relay-cropped with maize 4 to 5 weeks after maize is sown. Relay cropping minimizes negative effects of the woody perennials on crops while allowing the woody perennials to benefit from fertilizer and weeding provided to the crops. The practice also permits the growth of the woody perennials to be extended to two instead of one season. When the crop is harvested at the end of the first season (July-August), the woody perennials are left

to grow during the second season until they are cut in February-March and the cropping cycle repeated.

Once the woody perennials are cut, wood is removed and the leaf and small twigs are left on the field and incorporated into the soil during land preparation. Such a fallow can provide 90 to 120 kg N/ha depending on rainfall during the fallow period. The source of this N could be N found accumulating in the subsoil of the soils of the study area (Hartemink *et al.*, 1996), N_2 biologically fixed from the atmosphere and N mineralized from the soil organic matter. The levels of nutrients provided through the foliage of the woody perennials in improved fallow systems is usually sufficient to produce 3 to 4 tonnes of maize per hectare. Inorganic nutrient inputs would, however, be required for higher yields and/or if the fallow biomass is used as livestock feed.

Inorganic fertilizers will also be required to supplement any short falls in what the organics (such as improved fallows and biomass transfer) provide. This may become necessary to sustain tithonia biomass production since it is not a legume that can biologically fix atmospheric N_2. To determine the sustainability of nutrient supply through tithonia biomass transfer, one has to consider the possibility that tithonia planted on the boundaries of the farms and contour bands could act as a trap for nutrients moving down the slope with water and soil. This would minimize the need for external inputs to sustain biomass production of tithonia which would also cycle back to the farm nutrients that would otherwise have been lost. What is required, therefore, is an understanding of nutrient acquisition mechanism by tithonia and redistribution of nutrients within the landscape through transfer of tithonia biomass. Long-term studies or farm nutrient budgets may also help determine the sustainability of tithonia-use systems.

Another important component of the package extended to farmers in the pilot project is soil conservation without which most of the P applied could be lost through soil erosion on sloping lands. Fortunately, there are well-proven biological erosion control options, such as contour hedgerows with leguminous species and grass strips (Kiepe and Rao, 1994) which also provide useful products in the form of fodder or organic inputs for green manuring of adjacent fields. The increased plant cover from P input alone can also reduce loss of soil nutrients. For example, in an experiment in Western Kenya on slopes of 3–4%, application of 500 kg P/ha reduced soil erosion and the loss of total P was not higher than that under unfertilized maize (Jama, 1999). While the high P rate used in this study may not be recommendable for resource-poor farmers now, it reflects one of the approaches to replenish the P depleted soils (one time application of a large amount). It could, however, become an option for farmers if and when fertilizers become affordable through either a subsidy program or improved structure and marketing conditions.

About 4000 farmers are currently testing and adapting improved fallows many with integration of Minjingu PR. Another 1400 or so farmers are also testing tithonia biomass transfer, many also in combination with Minjingu PR. Farmers are extremely pleased with the results, as their crop yields have increased many folds. The farmers are also testing these technologies on many crops – maize, maize and bean intercrops and on vegetables such as 'sukuma wiki' (Kale: *Brassica oleraceae*) and tomato. Tithonia biomass transfer can be labor intensive but its use on such crops as kale that are higher-valued than maize make its use attractive to farmers (ICRAF, 1997).

Conclusion

Soils in the tropics are renowned for low soil fertility particularly low nitrogen. Consequently low soil fertility ranks as the second most important abiotic constraint to maize production in the subhumid zones after drought. Intensified land uses, and the rapid declines in fallow periods, coupled with extension agriculture into marginal lands, have contributed to rapid decline in soil fertility particularly in the high potential subhumid zone.

Nitrogen and phosphorus deficiencies are severe and widespread biophysical constraints to smallholder maize productivity, and in turn to long term food security of the resource poor in Southern and Eastern Africa. Crop rotations, intercropping, improved fallows, green manures, inorganic fertilizers and integrated nutrient management practices (organic and inorganic nutrient source) have been developed as a means of replenishing soil fertility and increasing maize productivity. In our conclusion a critique of which technologies will be widely adopted is given.

Inorganic fertilizers have been recommended as a quick means for increasing maize productivity. Where smallholder farmers apply fertilizers, the quantities applied are too low that they contribute little on long term fertility management. It has been calculated that farmers apply an average of 10 kg/ha for fertilizer nutrients. The high grain to nutrient price ratios and high levels of production risk are two of the underlying factors of the low fertilizer use. Even when fertilizer is used in farmer's fields the nutrient use efficiency is very low and this also reduces overall productivity. Progress has been made in developing maize cultivars which efficiently utilize soil available nutrients especially nitrogen and covert it to grain. It is estimated that N-use efficient cultivars could increase maize yield gains by 25%. Further increase of farm yields must come from enhanced and more efficient use of chemical fertilizers and organic manures and adoption of agronomic practices that increase fertilizer responsiveness such as early planting and appropriate land management practices.

A central aspect of sustaining soil fertility on smallholder farms is the maintenance and management of soil organic mater (SOM). Inorganic fertilizers do not add organic carbon in the soils unless the crop residues are ploughed back in the soil. Organic inputs from crop rotations and other techniques will contribute to some maintenance of SOM.

Crop rotation with annual grain legumes offer much higher opportunity for widespread adoption. These annual legumes offer a good compromise for meeting both food security and soil fertility needs for farm household. Grain legumes can provide seed and sometimes leaves for home consumption, income while adding organic matter and nitrogen to the soil. The most promising species combine high grain yield, high root and short biomass and low nitrogen harvest index. Such legumes include self-nodulating promiscuous types of soyabean, pigeon pea, groundnut, cowpea and bambara nuts. Under favourable conditions green manure crops can generate large amounts of organic matter (up to 200 kg N/ha) in 100-150 days of growth of which 30-50 kg are available to crop growth. Although there is a long history of experimentation with green manures for improving soil fertility in Southern and Eastern Africa, the adoption rate by smallholder farmers is very low or none. However, promising research results from the Soil Fertility Network (SOILFERTNET) of Southern Africa on green manures have started to emerge. The on-going research is focussed on the potential of undersowing maize with green manures for improving soil fertility. Undersowing *Tephrosia vogelli* appears to be one of the most promising as it grows through the dry season and produces a large amount of organic matter. Velvet beans have also shown good potential for use as a green manure in rehabilitation of exhausted soils and are able to produce large amounts of biomass under acidic soils.

Improved fallows are the most promising agroforestry basal soil fertility replenishment systems in both Southern and Eastern Africa. This practice has been adopted in extensive farming system such as Eastern Zambia and intensive land use systems in Western Kenya. About 30 000 farmers are experimenting with improved fallows in these two regions. In addition to supplying nitrogen and improving maize productivity, tree fallows provide other benefits. Fuelwood production is on the order of 15 t/ha^{-1} after 2 year sesbania fallows. *Sesbania sesban* and other tree fallows have decreased the seed pool of parasitic weed *Striga hermonthica* by 50% in Western Kenya and Eastern Zambia. Tree fallows can also relay other nutrients such as potassium from depth and improve soil physical properties such infiltration rate aggregate stability and water storage. A lot of NGOs are disseminating improved fallow for soil fertility replenishment in the region. However there are several concerns which need to be addressed. Improved fallows may not be an option for a larger number of farmers with small land holdings. Low soil fertility and pests can reduce the biomass produced by fallows.

There are also no clear answers on how much N is fixed by trees on different soil types and unless this is addressed improved fallows may produce inadequate N for high maize yields. There is need to continue evaluating different fallow species, management and adoption across biophysical and socio-ecomic gradients. The institutional support required for wide adoption of fallows needs to be understood.

There are no silver bullet solutions for soil fertility replenishment. Various options suit farmers depending on their biophysical and socio-economic circumstances. The promotion of integrated soil fertility management practices seems to offer much potential than promoting one or two options. For these technologies to make an impact on-farm income and livelihood there several issues which need to be addressed. These include seed production, pest species diversity and microsymbionts of legumes. The strategy for scaling up different options should involve farmers, extensions, researchers, NGOs and policy makers. Without this concerted effort, researchers will continue to produce technological bullets in the institutional vacuum!

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