Nutrient Cycling in Agroecosystems (2006) 76:153–170
DOI 10.1007/s10705-005-7126-7

Available technologies to replenish soil fertility in East Africa

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Received 1 September 2004; accepted in revised form 2 May 2005

Keywords: Affordable, Fertilizers, Infertile soils, Replenishment, Technologies

Abstract

Low inherent soil fertility in the highly weathered and leached soils largely accounts for low and unsustained crop yields in most African countries. But in particular, the major nutrients, nitrogen (N) and phosphorus (P), are commonly deficient in these soils. This scenario of nutrient depletion is reflected in food deficits and hence the food aid received continuously, specifically in sub-Saharan Africa. Undoubtedly, substantial efforts have been made in the continent to replenish the fertility of degraded soils in attempts to raise crop yields, towards self-sufficiency and export. Such efforts consist of applications of both organic and inorganic resources to improve the nutrient status of soils and enhanced nutrient uptake by crops, provided that soil moisture is adequate. Overall, positive crop responses to these materials have been obtained. Thus in the East African region, maize (staple) yields have been raised in one growing season from below 0.5 t/ha without nutrient inputs, to 3–5 t/ha from various nutrient amendments at the smallhold farm level. However, in spite of the positive crop responses to nutrient inputs, farmers are generally slow to adopt the soil fertility management technologies. In this paper we review the impact of some technologies, focussing the use of nutrient resources of different characteristics (qualities) in relation to improved crop yields, with an overall goal to enhance technology adoption. Thus, inorganic resources or fertilizers often give immediate crop responses, but their use or adoption is rather restricted to large-scale farmers who can afford to buy these materials. Organic resources, which include crop residues, water hyacinth and agroforestry shrubs and trees, are widely distributed, but they are generally of low quality, reflecting the need to apply large quantities to meet crop nutrient demands. Moreover, most organics will add N mainly to soils. On the other hand, phosphate rocks of varying reactivity are found widely in Africa and are refined elsewhere to supply soluble P sources. The recently developed soil fertility management options in East Africa have targeted the efficient use of N and P by crops and the integrated nutrient management approach. Some people have also felt that the repackaging of inputs in small, affordable quantities, such as the PREP-PAC described in this paper, may be an avenue to attract smallhold farmers to use nutrient inputs. Nonetheless, crop responses to nutrient inputs vary widely within and across agroecozones (AEZs), suggesting specificity in recommendations. We highlight this observation in a case study whereby eight soil fertility management options, developed independently, are being tested side-

by-side at on-farm level. Farmers will be empowered to identify technologies from their own choices that are agronomically effective and economically friendly. This approach of technology testing and subsequent adoption is recommended for technology development in future.

Introduction

It is widely known that variations in altitude, climate and soils largely influence agricultural productivity within and across countries in Africa. These variations have been used in the sub-divisions of croplands into agroecozones (AEZs) for management purposes in each country. Thus in the eastern African region, low maize (staple) yields are common in the coastal, medium altitude and moisture stressed regions, whereas high yields occur on the cooler high altitude and high rainfall areas (Table 1). Crop yields certainly are dependent on the management factors, but low yields are widespread on the highly weathered and nutrient depleted soils (e.g. Table 2 soils) in Africa, mainly the acrisols (ultisols), ferralsols (oxisols), nitisols and luvisols (alfisols) (Woomer and Muchena 1996). In the studies of nutrient cycles at the continental (Sanchez et al. 1997), district (Smaling et al. 1997) and farm (Shepherd et al. 1996) scales, major nutrient (nitrogen, phosphorus, potassium) outflows far exceed inflows in a range of farming systems in most countries in Africa, resulting in the well-known negative nutrient balances.

These nutrient deficits (nutrient depletion) are reflected in the overall low and declining crop yields (Figure 1), suggesting long term food deficits and hence food aid in sub-Saharan Africa (see Table 3 for Kenya). Gachene and Kimaru (2003) have gone a step further to pinpoint soil related constraints that contribute to nutrient depletion, low land productivity and low crop yields in Africa; these are: low soil moisture, soil salinity

Table 1. Maize growing areas in Kenya by agro-ecozones (AEZs, after Ayaga 2003).

Growing area	AEZ	Altitude (m) a. s. l.	Area (×1000 ha)	Mean maize yield (t/ha)
Coastal zone	CL3/CL4	0–1000	100	1.36
Moisture-stressed	UM/LM	1000–1600	400	1.03
Non-moisture stressed (mid altitudes)	UM/LM/LH	1600–1700	400	1.44
High altitude late maturity	UM/UH	1700–2300	500	2.91
Very high altitude	UM	2300	100	2.76
Total	–	–	1500	–

Legend CL – Coastal lowlands 3 and 4.
UM and LM – Upper and Lower Midlands.
UH – Upper Highlands.

Table 2. Some properties of soils from maize growing areas in East Africa (after Okalebo, 1987).

Soil parameter	Medium to high altitude		Low altitude including ASALs	
	Mean	Range	Mean	Range
pH (0.01 M $CaCl_2$)	5.15	4.64–5.72	5.14	4.56–6.10
Total N (%)	0.25	0.12–0.52	0.11	0.08–0.15
Total C (%)	2.5	1.1–4.0	1.0	0.8–1.4
CEC (cmol kg^{-1})	19.0	11.8–26.5	10.8	5.4–16.4
Olsen available P (mg kg^{-1})	40	17.3–54.1	21	9.2–40.7

Number of sites for medium to high altitude soils = 14.
Number of sties for low altitude soils = 10.
ASALs = Arid and semi-arid lands.
Note: Low N and C (organic matter contents), the CEC and the clay contents of the soils from the low altitude, including ASALs areas.

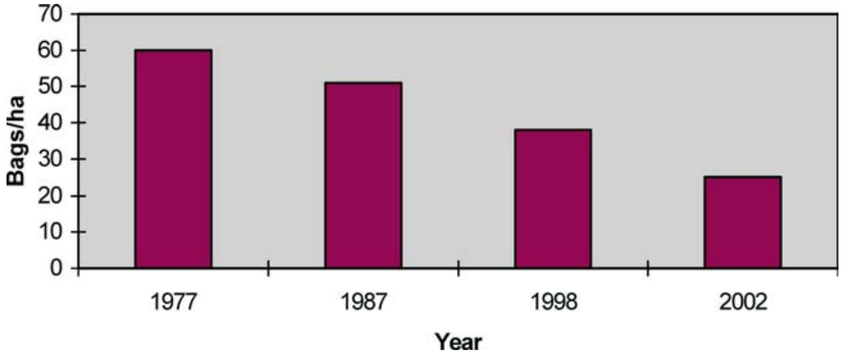

Figure 1. Maize yields in Trans Nzoia district (1977–2002). Source: Rev. (Nelson Kariuki (2003), CENART CONSORT NGO. Note: One bag weighs 90 kg of sun-dried maize grain.

Table 3. Projected deficits in the food commodities in Kenya in the year 2010 (after Ayaga 2003).

Commodity	Annual deficit (×1000 t)
Maize	864
Wheat	251
Rice	161
Vegetable oils	291
Sugar	100

and sodicity, soil compaction and formation of hard pans common in drylands. To improve agricultural productivity, rather extensive research efforts have been made in most areas in Africa to replenish the fertility of nutrient depleted soils. These include the diagnostic investigations to pinpoint nutrient limitations, the identification of both inorganic and organic inputs and their rates, times and methods of application, use of low cost inputs and the agroforestry based systems to recycle nutrients. Results from these soil fertility studies are enormous, but summaries by (Sanchez et al. 1997; Lwayo et al. 2001), Gichuru et al (2003) and Bationo (2004), are very useful.

In this paper, we highlight soil fertility management technologies developed and practiced in the East African region. We recognize the need for site-specific fertilizer or manure recommendations for major crops as a result of variability in the nutrient status of soils within and across croplands (Okalebo et al. 1992). We present case studies, which pinpoint the materials and their rates of application in soil fertility replenishment, together with the results obtained from technologies. We also recognize and highlight the economics impact on technology adoption in the East African region.

Our main objective in this paper is to expose and summarize a range of soil fertility management options, together with data associated with each option, which will empower the farmer to adopt a specific technology. It is envisaged that the review will guide researchers in their efforts to find the way forward towards soil fertility amelioration and enhanced food security.

Early studies on soil fertility replenishment in East Africa

Crop responses to inorganic fertilizers

The constraint of soil fertility depletion was probably appreciated in most African countries from about 1950s to date. Before this period, shifting cultivation was widely practiced, whereby the bushy to forest lands were cleared and cropped until yields fell; the farmers then moved to other bushy lands and thereby allowed the exhausted land to rebuild fertility through long fallows (e.g. Cooke 1967; Greenland 1974). This shifting cultivation practice is still used in the forest lands in Central Africa and Nigeria, where bushes and forests are slashed down and burnt to facilitate cultivation (Gichuru et al. 2003). However, as a result of population pressures from about 1980s to date, particularly in the eastern African region, land has been cultivated continuously with negligible to no nutrient returns to land (Smaling et al.

1997; Swinkels et al. 1997), resulting in soil fertility depletion constraint outlined above. In this subsection, we summarize results from diagnostic efforts to detect nutrient limitations in soils and solutions to correct these constraints, using mainly the inorganic resources.

Thus, laboratory analysis of soils (Birch 1952; Stephens 1961; Uriyo et al. 1976) and pot tests (Pinkerton 1958; Butters 1961) have been widely used in East Africa to detect nutrients limiting plant growth, while field trials (a few selected and presented in Table 4) have confirmed the nutrient limitations from the laboratory and pot tests. However, the common feature of these early trials is that they indicate wide responses to applied nitrogen (N) and phosphorus (P) fertilizers, but give limited to no economic based recommendations for fertilizer types and rates.

In the early study approach, experimentation varied widely among researchers and the AEZs including soils, sites, and soil characterization was minimal. Types and rates of fertilizer N and P also varied significantly, influencing responses to a wide variety of crops (mainly the cereals). Limited economic analyses in only cost to value ratios were done.

This early study approach has mainly contributed to blanket kind of fertilizer recommendations, for example, the 60 kg N + 26 kg P/ha recommended for maize in many parts of Kenya, irrespective of factors such as soil type, rainfall regimes and cropping history. From 1990s to date, there has been a shift in research to restore soil fertility in the eastern African region. Tasks have delineated the need to identify specific nutrient limitations within and across fields in a farm (Okalebo et al. 1992; Ikombo et al. 1994; TSBF 1994). This approach permits the narrowing down or the reduction of treatments needed for specific crop responses for the specific area. It also targets the production of packages for target areas, such as the PREP-PAC package (described later in this paper) that replenishes the fertility of seriously depleted patches in a field.

In another development, the organic resources that are commonly available and therefore widely used by the African smallhold farmer to restore soil fertility have been characterized with respect to their quality Woomer et al. 1994a; Probert et al. 2004). The outstanding results are that the organic materials vary widely in quantity and quality (nutrient, lignin and polyphenolics contents) as illustrated in Table 5. The materials are generally very low in quality (compared to inorganic materials). But TSBF suggests the direct use of the organic resources containing total N levels above 2.5% N, towards the affordability constraint (Palm et al. 2001).

In addition to low cost organic materials, short duration fallows (e.g. sesbania, tephrosia,

Table 4. Crop responses to inorganic fertilizers from selected field trials.

Source	N and P rates	Crop	Response
Kenya (1970–1994)			
Gathecha (1970)	50–500 kg P/ha SSP	Sorghum, wheat, maize	+ve
Vadlamudi and Thimm (1974)	174 kg N + 105 kg P/ha TSP	Maize	+ve
Allan et al. (1972)	170 kg N + 26 kg P/ha DAP & TSP	Maize	Economical +ve
Allan et al. (1972)	60 kg N + 26 kg P/ha TSP	Maize	Economical
FURP (1994)	75 kg N + 26 kg P/ha TSP	Maize	Economical
Probert and Okalebo (1992)	60 kg N + 20 kg P/ha TSP	Maize	Economical
Tanzania (1963–1984)			
Evans (1963)	50–100 kg P/ha TSP	Maize and groundnuts	+ve
Anderson (1970)	50 kg P/ha DAP	Maize	+ve
Marandu et al. (1973)	40 kg P/ha TSP	Maize	+ve
Mongi et al. (1974)	100 kg N + 40 kg P/ha TSP	Rice	+ve
Ngatunga (1964)	40 kg N + 44 kg P/ha TSP	Maize	Economical
Uganda (1967–1973)			
Stephens (1967)	100 N + 85–225 kg P/ha TSP	Maize and groundnuts	+ve
Foster (1973)	ON + 11 kg P/ha SSP	Wheat	Economical
Foster (1973)	53 N + 25 kg P/ha SSP	Maize	Economical
Shumaker and Ogolle (1967)	100 kg N + 22 kg P/ha TSP	Sorghum, millet	+ve
Starks et al. (1971)	100 kg N + 22 kg P TSP	Sorghum	+ve

Table 5. Nutrient contents of commonly available organic resources among smallhold farmers in Central Kenya. (Woomer et al. 1999a).

Resource	Nutrient content (% dry matter)				
	N	P	K	Ca	Mg
Napier grass	1.02	0.11	2.63	0.35	0.06
Maize stover	0.89	0.8	2.78	0.41	0.18
Bean trash	1.20	0.13	2.06	0.89	0.16
Cowpea trash	0.57	0.05	1.79	0.81	0.08
Pigeon pea prunings	1.33	0.10	1.02	0.37	0.09
Sweet potato vines	2.27	0.14	3.05	1.32	0.53
Cattle boma manure	1.40	0.20	2.38	0.39	0.27
Poultry manure	3.11	0.42	2.40	0.82	0.42
Goat/sheep manure	1.48	0.20	3.31	0.94	0.42
Domestic compost	1.34	0.20	1.82	0.39	0.22

crotalaria), have been identified and tested by ICRAF to recycle nutrients and to add the most limiting N nutrient to soils through the biological nitrogen fixation (BNF) process and also through incorporation of their biomass into soils (Jama et al. 1997; Ndungu et al. 2003) and subsequent N release.

In the presentation of soil fertility management options used to replenish soil fertility in Eastern African region, the resources, together with their qualities and quantities, are given, focussing their uses to improve and sustain crop yields under the widely practiced maize–legume intercrops, banana and agroforestry cropping systems in the region. A few recently developed managements will highlight the impact of economic analysis/data designed to show profits or losses arising from using specific soil fertility options. It is felt that profitability is a good indicator towards the adoption process of technologies, particularly to the smallhold farmers who constitute over 80% of the farming communities in the developing world. The options now follow.

The impact of organic resources on soil fertility restoration

Addition of organic materials to soil is known to improve the chemical, physical and biological properties that will enhance the availability of nutrients and their uptake by crops.

In Table 5, a wide range of organic resources at farm level have divergent qualities and these materials will decompose and release different quantities of nutrients in soils at different times (Gachengo et al. 2004), reflecting differences in nutrient availability and overall crop yields from each resource.

High quality materials, such as poultry manure, will therefore mineralize more readily in soils compared to low quality materials such as maize stover. Nonetheless, the mineralization and nutrient release patterns of low quality organic resources may be manipulated through incorporation of inorganic or through decomposition through the composting process (Muasya et al. 1996). This background information is supported by the findings from specific composting and soil fertility restoration tasks carried out in Kenya and Uganda, now described.

Crop responses to inorganic resources

The role of manure for improving soil fertility with reference to ASALs

In the ASALs, water (soil moisture), nitrogen and phosphorus significantly limit crop productivity (Keating et al. 1992). Surface management technologies in these fragile areas and soils have been suggested and tested to enhance moisture and nutrient storage for their efficient utilization, with positive results (Probert and Okalebo 1992).

Manures provide both N and P and other nutrients, but they are present in less soluble forms than in inorganic fertilizers. The crop response obtained will therefore, depend upon the deficiencies that occur in the soil and the rate at which nutrients in the manure are made available.

In studies carried out by J. R. Okalebo (unpublished data), an attempt was made to separate the effects of N and P by including treatments that compared their effects (alone or combined) with those obtained with poultry manure and farmyard manure (FYM) available at farm level. However, there were only single rates of application of each fertilizer material (due to field size limitations at on-farm level). The results from these on farm sites were similar and the means are presented in Table 6. In no instance was the response to separately applied N or P significant, making it impossible to determine which of the nutrients in the manure caused the responses. When N and P were applied together, yields were similar to those obtained with the FYM and poultry manure.

Table 6. The effects of fertilizers and manures on the yield of maize grain (kg/ha) averaged over three ASAL sites in eastern Kenya (Probert and Okalebo 1992).

Treatment	First season 1979	Second season 1979	
		With fresh application of fertilizer	Initial application only
Control	2.34	1.51	1.34
CAN (60 kgN/ha)[a]	2.38	1.33	1.05
TSP (40 kg P/ha)[a]	2.23	1.77	1.43
CAN + TSP	3.21	1.88	1.39
FYM[b]	3.08	2.21	1.77
Poultry manure	4.00	1.97	1.79
SE	(1.09)	(0.91)	(0.95)

[a] Sources of N and P were calcium ammonium nitrate (CAN) and triple superphosphate (TSP)

[b] The FYM used was not the same at all sites. Rates of N and P applied (kg/ha) in the FYM treatment were: at Kathonzweni and Kampi ya Mawe sites (Kenya) were 103 N and 44 P, at Kimutwa site 215 N and 49 P.

The poultry manure applied was 106 N and 58 P (based on chemical analysis of materials).

Residual effects following a single application of the fertilizer materials tended to be greater for the manures than in the organic sources, but yields were below what could be achieved with fresh application of the manures. Nevertheless, the nutrients responsible for residual effects are not necessarily the same as those causing responses when freshly applied.

This experiment was comfounded by many variables. Nonetheless, it gives an insight on complexities involved in handling organics with different qualities. In practice, farmers apply moist manures (some not completely decomposed) in measures of handfuls/planting hole or in wheelbarrow loads (Probert et al. 1992).

Use of water hyacinth (Eichornia crassipes (Mart.) Solums) as an organic input to soils in Uganda

In Uganda, bananas (Musa) are grown on a wide range of soils, but mainly on the degraded ferralsols along Lake Victoria basin. Apart from soil moisture conservation, the mulches (mainly from banana residues) also provide nutrients to growing bananas. Thus banana yield increases have been obtained from retention of crop residues and addition of 10 t/ha of napier grass or as cattle manure (Woomer et al. 1999b).

The invasion of water hyacinth into lakes, and rivers of East Africa has forced the implementation of mechanical clearing around the shores and dams, resulting in difficulties of waste disposal, particularly on crowded areas (Amoding et al. 1999). Water hyacinth therefore, presented an opportunity to apply organic inputs to agricultural soils of low inherent fertility. Part of the study on the utilization of the water hyacinth examined the composting of wastes as a means of concentrating plant nutrients and the consequent growth response to the compost by the high value cabbage crop. Water hyacinth has been used as a soil additive to agricultural systems as mulch and compost, for example as mulch to tea estates in India (Gopal 1987). Earlier investigations along the shores of Lake Victoria in Uganda indicated that when water hyacinth is applied as mulch, it offers an opportunity as an organic input to soils because of its high nutrient contents and its rapid decay pattern (Amoding et al. 1999). An estimate of 209 t of N is contained in water hyacinth recovered through mechanical clearance at the Owen Falls Dam in Jinja, Uganda. Further, the compost made from water hyacinth contains higher major nutrients than that prepared from cattle manure (Heider et al. 1984).

Composting concentrates nutrients and hence reduces transportation costs of the high water (92%) containing fresh water hyacinth. Results of an experiment where the benefits of fresh and composted water hyacinth were compared as organic inputs to degraded soils around Lake Victoria in Uganda are summarized here. Compost was prepared from dewatered, chopped water hyacinth using the pit method. Composting resulted in an increase in the N content.

The effects of the compost were compared with those of fresh water hyacinth applied as either

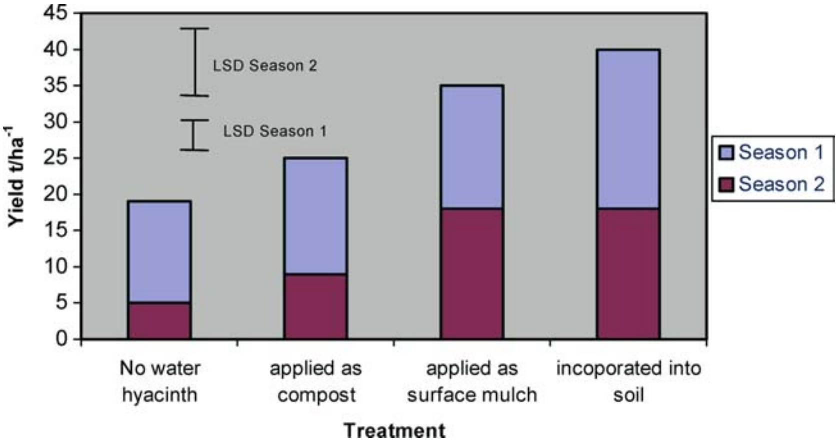

Figure 2. Effect of water hyacinth amendments on cabbage yield (Amoding et al. 1999).

mulch or incorporated into the soil and to a control receiving no inputs (Figure 2). When the costs of chopping and application are considered, fresh water hyacinth wastes give higher benefits than the composted wastes (Amoding et al. 1999). This organic input will continue to be available as long as it keeps on moving across Lake Victoria.

Use of wheat straw, soybean trash and nitrogen fertilizer for maize production in the Kenya Highlands

Making best use of available crop residues is an important component of integrated nutrient management. In the wheat growing areas of Kenya, wheat straw, yielding up to 15 t/ha, is left in the fields and burnt to facilitate land cultivation for the succeeding season. A field study was conducted over two seasons (1997 and 1998) in Kenya (Uasin Gishu district) that examined use of wheat straw, soybean trash and N fertilizer as nutrient inputs for maize production. The organic inputs were applied at the rate of 2 t/ha per season and urea was added at rates of 0, 20, 40, 80 and 100 kg N/ha in an incomplete factorial treatment structure that also included a complete control (no inputs) and 80 kg N/ha as urea without organic inputs. Urea was meant to enhance the decomposition of wheat straw. Rate of 2 t/ha straw as chosen not to cause N immobilization when incorporated into soils.

Maize grain yield ranged between 0.75 and 6.84 t/ha in 1997 with lowest yields observed in the treatment receiving wheat straw alone, and higher yields associated with soybean residue incorporation. There was benefit from more favourable rainfall, providing grain yield increase of 141% above control treatment as a result of combining 2 t/ha soybean trash and 100 kg N/ha urea (Table 7).

The generally high yields from soybean trash are explained in terms of higher quality, faster decomposition and nutrient release compared to lower quality wheat straw. A positive effect in increases of soil pH, C, N, and P status as a result of cumulative use of crop residues was observed.

Larger yields were obtained when organic and inorganic inputs were applied together to soils,

Table 7. Effect of continued application of crop residues and nitrogen fertilizer on maize grain yield (t/ha) in a Chepkoilel ferralsol, Eldoret, Kenya (after Okalebo et al. 1999).

Treatment	1997	1998
Control	0.87	2.83
80 N	1.02	4.88
WS + ON	0.96	2.05
WS + 20 N	1.32	2.93
WS + 40 N	1.30	3.22
WS + 80 N	1.67	4.79
WS + 100 N	1.68	5.47
SYT + ON	0.75	2.83
SYT + 20 N	1.47	2.50
SYT + 40 N	1.44	3.71
SYT + 80 N	1.50	5.57
SYT + 100 N	1.88	6.84
LSD ($P = 0.05$)	555	1030

NB: WS, Wheat straw; SYT, soybean trash.
N, nitrogen applied as urea at 0, 20, 40, 80 and 100 kg N/ha.

particularly when soil moisture was adequate and from addition of organic inputs higher in mineralisable nutrients. These findings suggest that better use may be made of crop residues than the burning following harvest as is it currently practiced by many farmers in this wheat growing area of western Kenya (Okalebo et al. 1999). Added N enhances straw decomposition and N release.

Using a wide range of organics and inorganics to replenish soil fertility in central and eastern highlands of Kenya

Like most African countries, soil fertility depletion largely accounts for low and declining crop yields in eastern and central highlands of Kenya.

Use of inorganic fertilizers in this region is generally low, below 20 kg N and 10 kg P/ha (Muriithi et al. 1994). This amount of fertilizer is inadequate to meet crop nutrient requirements for optimum crop yields at on-farm level. Over 80% of the smallhold farmers use farmyard manure (FYM) to improve soil fertility and crop productivity. Maize yields at farm level hardly exceed 1.5 t/ha (Wokabi, 1994). Positive crop yield increases have been reported as a result of applying the biomass of tithonia, calliandra and leucaena for soil fertility improvement (Gachengo et al. 1999; Mutuo et al. 1998).

These materials needed evaluation in the field particularly for demonstration purpose to smallhold farmers. The demonstration used was researcher–farmer managed in Meru area, Kenya. A wide range of organic resources (mainly agroforestry shrubs/trees and manures) was compared through their incorporation into soils at an equivalent rate of 60 kg N/ha, the rate considered economical for optimum maize growth and yield in the candidate areas. The organics were also combined and incorporated into soils with inorganic compound fertilizer (23–23–0) at 30 kg N/ha, while the other 30 kg N/ha was obtained from the specific organic sources. Detailed experimentation is described by Mugendi et al (2001). The trial was conducted in two seasons in the year 2000. Maize grain yields obtained are presented in Table 8. Very low yields in the first season are explained in terms of low rainfall (total 126 mm) in that season compared to high yields in the second season, with a total rainfall of 698 mm.

Overall, the results of two seasons from this trial indicate that maize performance may be improved by combining fast decomposing plant biomass and half the recommended rate of N. Tithonia biomass with half of N (30 kg N/ha) gave the best results (6.4 t/ha) of maize grain in two seasons, followed by sole tithonia biomass (6.2 t/ha) then cattle manure with half the recommended rate of inorganic N (6.1 t/ha). The crotalaria gave the lowest yields (2.5 t/ha).

In this study the sole mucuna treatment had the highest benefit cost ratio of 4.1, followed by sole leucaena, sole crotalaria and sole tithonia. The recommended rate of inorganic N gave the lowest benefit–cost ratio of 1.6.

Table 8. Maize yields (t/ha) under different soil fertility amendments in Meru, Kenya.

Treatment	First rains 2000	Second rains 2000	Total
Control	0.8	3.6	4.4
Mucuna 60 kg N/ha	1.2	3.1	4.3
Crotalaria 60 kg N/ha	0.9	1.6	2.5
Mucuna 30 kg N + 30 kg N/ha	1.4	3.7	5.1
Crotalaria 30 kg N + 30 kg N/ha	1.0	3.6	4.6
Cattle manure 60 kg N/ha	0.9	4.9	5.8
Tithonia 60 kg N/ha	1.2	5.0	6.2
Calliandra 60 kg N/ha	0.7	4.5	5.2
Leucaena 60 kg N/ha	1.0	4.6	5.6
Cattle manure 30 kg N + 30 kg N/ha	1.2	4.9	6.1
Tithonia 30 kg N + 30 kg N/ha	1.3	5.1	6.4
Calliandra 30 kg N + 30 kg N/ha	1.0	4.4	5.4
Laucaena 30 kg N + 30 kg N/ha	1.3	4.5	5.8
60 kg N/ha (inorganic)	1.4	4.7	6.1
Mean	(1.1)	(4.2)	
SED	0.2	1.2	

(*Source*: Mugendi et al. 2001).

Table 9. Estimated resources of important phosphate rocks (PRs) in East Africa (after Buresh et al. 1997; Van Kauwenburgh, 1991).

Country	Name of deposit	Type of PR	Reactivity	Estimated reserves (10^6 tonnes)	Total P content (g/kg)
Tanzania	Minjingu	Sedimentary	Medium to high	10	87–109
Tanzania	Panda Hill	Igneous	Low	125	26
Uganda	Sukulu Hill	Igneous	Low	230	48–57
Kenya	Rangwe	Igneous	Low	–	<48

Nutrient replenishment using low cost phosphate rock and the biological nitrogen fixation process

Phosphate rocks

Phosphate rocks (PRs) have been used directly over a long period in Africa to improve the P status of soils and hence increase crop yields. Thus in the eastern African region different kinds of PRs are found with different parent rock origins, qualities and quantities in terms of P contents (Table 9).

About 51,000 tonnes of Minjingu PR (MPR) were mined in 1995. Total P contents of this PR vary rather widely. Currently the KEL Chemical Company in Thika, Kenya, imports MPR for the manufacture of single superphosphate for the Ugandan Market mainly and for direct use on coffee, tea and other crops (Paul Mwaluko, personal communication).

Effectiveness of these PRs in relation to crop yields in the eastern, central and southern African regions is generally around 69% compared to that of refined or soluble triplesuperphospahte (TSP) (Okalebo and Woomer 1994). But notably the biogenic/sedimentary MPR has attained 114% effectiveness compared to TSP on the acid and low P status soils of western Kenya (Buresh et al. 1997; Nyambati 2000). This level of effectiveness of MPR was found in the ICRAF experiments on acid and low P soils whereby a one-time replenishment of MPR at 250-kg P/ha was compared with annual MPR applications at 50 kg P/ha. Similar TSP addition rates were used for comparisons.

Using the PREP-PAC[1] technology to restore the fertility of depleted soils

Following the evidence above on the effectiveness of MPR on acid and low P soils, a package, PREP-PAC, was developed at Moi University, Eldoret, Kenya, in 1997, designed to replenish the fertility of soils on seriously depleted patches that are widespread on smallhold farms. PREP-PAC consists of 2 kg MPR, 0.2 kg urea, 120 g food legume seed, rhizobial inoculant (Biofix) packed with lime pellets to raise the pH of the inoculated seed environment and gum Arabic sticker to hold the inoculant onto the surface of the seed and instructions for use written in English, Kiswahili and local dialects. One packet is designed to replenish soil fertility of patches of size 25-m^2 (Nekesa et al. 1999).

Since 1997 on-farm trials have been conducted in western Kenya and eastern Uganda to test the effectiveness of PREP-PAC with respect to crop yields and economic considerations; these experiments are:

On-farm testing of PREP-PAC

Through the researcher-NGO-farmer contact, the target soils for replenishment were:

(i) Acrisols with sandy surface horizons and very low soil fertility (common in Siaya and Busia districts, Kenya).
(ii) Acrisols with clay surface horizons and low to moderate inherent soil fertility (common in Bungoma and northern Kakamega districts, Kenya).
(iii) Acrisols/ferralsols complexes with moderate to high clay contents, but now depleted inherent soil fertility (common in Vihiga and Kakamega districts, Kenya).

PREP-PAC was tested on smallhold maize–legume based intercropping systems in the depleted soils and districts above in western Kenya and some packs in eastern Uganda. Soils at the study sites had generally low soil fertility (Table 10) and the farmers considered these the most fertility-depleted areas of their farms (Nekesa et al. 1999).

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[1] PREP stands for Phosphate Rock Evaluation Project

Table 10. Selected soil (0–20 cm) chemical properties for 52 farms in western Kenya (Nekesa et al. 1999).

Soil property	Minimum	Maximum	Mean	Sd
pH (H_2O)	4.68	7.26	5.44	0.52
% N	0.15	0.49	0.32	0.08
% C	0.38	4.20	1.89	0.81
Olsen P (mg/kg)	1.00	7.50	2.40	1.50

PREP-PAC input was provided to 52 farmers in western Kenya and the prescribed application procedure explained. All farm operations, including application, plant disease/pest control were done by the farmers. Two adjacent plots each measuring 25 m^2 were marked and treatments applied to one plot. Inoculated bean seed and maize were planted immediately. Control plots were beans and maize intercropped with no PREP-PAC inputs.

Treatments were designed to compare economic returns to PREP-PAC with no fertility amendment practices in the bean–maize intercrops. In both treatments farmers planted the same maize variety of the farmers' choice and either climbing (cv Flora) or bush variety of *Phaseoulus vulgaris* contained in the PREP-PAC. Farmers managed the experiment (including the trials in eastern Uganda).

After harvest, sun-dried weights of maize and bean grains from two plots at each farm were taken. Statistical analysis of crop yield and economics data was done on the computer using SYSTAT package and FREELANCE package for the graphics. Maize yields were lowest in the unfertilized (control) plots with a mean farm yield of 0.64 t/ha. PREP-PAC application increased maize yield to a mean of 1.36 t/ha. PREP-PAC application to soils of pH < 5.2 improved bean yield from 25 to 125 kg/ha. This is obviously a very low bean yield. Nonetheless, this low pH level favours the dissolution of phosphate rock in soils. At the pH < 5.2, climbing beans (cv Flora) yielded 200 kg/ha on the control plots and the PREP-PAC yield was 350 kg/ha. Economically, use of PREP-PAC in soil pH < 5.2 increased financial return on land from Ksh. 8720 to Ksh. 19,920/ha, with a return ratio of 1.27 (Woomer et al. 2003a).

Testing the effectiveness of components of PREP-PAC

The performance of PREP-PAC components and their interactions were tested at three on-farm sites with low soil fertility in western Kenya (Obura et al. 1999). This region is also characterized by having two cropping seasons annually. Thus a $2 \times 2 \times 2$ factorial arrangement of MPR, Urea and inoculant (at 2 levels each) treatments was used in this experiment (with treatments applied in a randomized complete block design with four replications). Plot size was 25 m^2, reflecting the target areas for replenishment using one PREP-PAC. Treatments determined the response of maize and N-fixing soybean intercrops to individual components of the pack (MPR, Urea and Biofix) and the interaction of various components of the Pack (rock P + Urea, rock P + Inoculant, Urea + Inoculant, and rock P + urea + inoculant).

MPR (2 kg) and urea (0.2 kg) were broadcast and incorporated to 0–15 cm seedbed at planting. Soybean seeds (cv Black Hawk) were inoculated for specific treatments for planting. Maize was planted and the standard crop husbandry practices maintained. Maize grain yields for one season (first rains 2001) are presented in Table 11. Thus, the main PREP-PAC components (PR, urea and Biofix) applied individually increased maize yields across the three sites, but particularly so in Kakamega with red soil of a high clay content, where a grain yield increase of 162% above control treatment was found. The complete pack (PR + Urea + Biofix) gave the largest yield increase of 205% above the control in Siaya.

Positive economic returns to investment from individual PREP-PAC inputs and their combinations are reported elsewhere (Obura et al. 1999, Woomer et al. 2003a).

Marketing of PREP-PAC

For continuity of acquisition of components of the pack, a marketing study (Mwaura 2002) was conducted whereby the stockists and retailers of agricultural inputs in western Kenya were asked to sell the pack. Selling prices varied widely with farmers able to offer low prices (Figure 3). Economic studies on acquisition of inputs, repackaging, sales and profits need to be continued.

Extended use of Minjingu phosphate rock (MPR) for soil fertility improvement in Kenya

In our presentation on the use of PREP-PAC, we highlighted the MPR as being its major compo-

Table 11. Maize grain yield from three farms in western Kenya under maize - soybean intercrop (Obura, 2001).

Treatment	Grain yield (t/ha)		
	Siaya	Bungoma	Kakamega
Control	1.58	1.62	1.60
Biofix	2.23	1.25	2.26
Urea	1.93	1.18	2.61
MPR	2.51	2.44	4.17
Urea + Biofix	2.28	1.08	2.89
MPR + Biofix	2.93	2.41	2.95
MPR + Urea	3.74	3.03	2.30
MPR + Urea + Biofix	4.81	2.71	3.15
SED (trt)	(0.74)	(0.48)	(0.65)
LSD (P = 0.05)	1.53	(0.99)	1.35
cv (%)	26	24	24

MPR, Minjingu Phosphate Rock.

nent and we also stressed its applicability for amelioration of soil fertility in the worst patches in the fields, focussing the increase in yields of maize–legume intercrops (mainly beans and soybeans).

However, as indicated earlier, MPR is generally effective on acid and low P and Ca soils. Several researches have tested the effectiveness of MPR on a range of crops, including the agroforestry – short or improved fallows. Thus in a field study by Ndungu et al (2003) the use of low cost technology utilizing MPR as a P source to enhance the growth and yield of maize – short fallow intercrops on nutrient depleted soils, also aimed at the provision of low cost N to succeeding maize crops through the N fixed by the legume fallows (crotalaria and tephrosia) and through the fallow biomass decomposition and N release in soils. Apart from soil fertility replenishment, the fallows tested have also other uses, such as the provisions of poles, fuelwood and pest control (tephrosia). Three on-farm trials in Busia, Siaya and Bungoma districts, Kenya, tested the effectiveness of MPR (at 0, 20, 40, and 60 kg P/ha) on the yields of maize – fallow intercrops in the first cropping season of MPR incorporation.

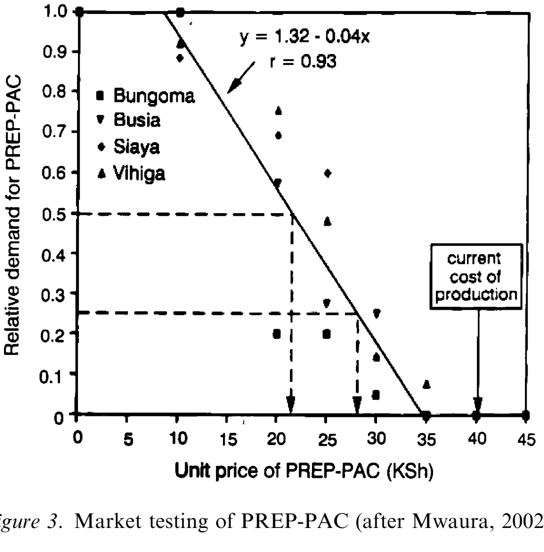

Figure 3. Market testing of PREP-PAC (after Mwaura, 2002).

In the second season, the effect of chopped fallow biomass incorporation with residual MPR, was monitored in relation to the release of mineral N (Table 12) through fallow biomass decomposition 16 and 32 weeks after maize planting (WAP) and the interaction with MPR. Maize yields were also obtained in the second season (Table 13). Treatments significantly increased NO_3–N levels in soils in all three sites, as shown for Siaya site (Table 12). Levels of nitrate in soils also increased with cropping period from 16 to 32 WAP, reflecting the availability of N over a long period during maize cropping.

In the first season, the treatments further significantly increased maize yields in all sites as given in Table 13 for Siaya. Low and insignificant grain yield increase in the second season is attributed to low and poorly distributed rainfall. Nonetheless, the net benefit and return to land from applying different rates of MPR varied with site. The highest net benefits were found in Bungoma site in the maize–bean rotation system when MPR was applied at 60 kg P/ha, giving the return to land values of Kshs. 15,758 over the two seasons. It is to be noted that due to a longer maize growing season in Bungoma (coolest site), only beans were planted at this site in the second season. This obviously raises the question of labour in relation to chopping and incorporation of fallow biomass ready for second season planting. There is a short period between harvesting of first maize crop and planting the second maize crop.

Nevertheless, MPR is effective on replenishing soil fertility for production of a wide range of crops, including short fallows, that will eventually provide additional N input to cropping systems. In a separate/parallel study by Kifuko et al (2003), chicken manure and maize stover mixed with MPR and incorporated into the seedbed significantly increased maize yields, raised the available P levels in soils and reduced P sorption in the same ferralsol of Siaya site.

Table 12. Effect of MPR and short fallow biomass incorporation into (0–15 cm) soils on NO_3–N during maize growth in Siaya (Kenya) site ferralsol, second season (Ndungu et al 2003).

MPR (kg/ha)	Sampling time, weeks after maize planting (WAP)					
	16 WAP			32 WAP		
	Crotalaria	Tephrosia	Mean	Crotalaria	Tephrosia	Mean
0	9.3	5.8	7.5	13.4	12.1	12.7
20	10.7	9.9	10.3	17.0	14.2	15.6
40	9.1	13.2	10.2	17.8	23.8	20.8
60	11.4	8.9	10.2	16.2	18.1	17.1
Mean	10.1	9.5	9.8	16.1	17.0	16.6

No statistical analysis was done on NO_3–N data, due to limited laboratory analytical facilities and hence composite samples from each of four replications for treatment were analyzed.

Replenishment of phosphorus in depleted soils in Tanzania using MPR

A comprehensive review by Semoka and Kalumuna (1999) on MPR research work conducted in Tanzania from 1960s has shown that MPR has agronomic effectiveness. Under favourable conditions of low soil pH, phosphorus, and calcium status of soils and high rainfall, MPR is as effective as the inorganic P fertilizers such as triplesuperphosphate. However, in most cases, conventional fertilizers were found to be better than MPR in the first year/season of application, but in subsequent seasons the effectiveness of MPR increased. Generally, from the third year of application onwards, the yields obtained from MPR addition were higher than those obtained from conventional fertilizers (Semoka and Kalumuna 1999). In any case, research with MPR has been limited in Tanzania to a few crops grown mainly in the subhumid areas. Mkangwe (2003) recognized the stated declining soil fertility status, the changing climate, and the new crop varieties with high nutrient demands, and thus carried out trials in the drier parts of central Tanzania to examine the effect of MPR from its direct and residual additions on the yields of the widely cultivated groundnuts and maize in that area and also compared the residual effects of MPR and TSP applications on maize yields.

Table 14 shows the groundnut yields obtained from six consecutive cropping seasons in central

Table 13. Effect of MPR and short fallow biomass incorporation into 0–15-cm ferralsol of Siaya (Kenya) on maize grain yields (t/ha) in two seasons (Ndungu et al 2003).

MPR (kg/ha)	First season			Second (successive) season		
	Fallow species			Fallow species		
	Crotalaria	Tephrosia	Mean	Crotalaria	Tephrosia	Mean
0	1.45	0.71	1.08	1.11	1.17	1.14
20	3.23	2.26	2.74	1.21	1.84	1.52
40	2.34	2.76	2.55	1.38	1.61	1.50
60	3.63	3.32	3.50	1.55	1.63	1.59
Mean	2.66	2.27	2.47	1.31	1.56	1.44
SED (P)	0.51			NS		
SED (F)	NS			NS		
SED (P × F)	NS			NS		

SED (P), Standard error of deviation for P rates.

SED (F), Standard error of deviation for fallow biomass.

SED (P × F), Standard error of deviation for interaction between P rates and fallow species biomass.

Table 14. Effect of MPR and TSP on seasonal groundnut kernel yield (t/ha) in central Tanzania (adapted from Mkangwe 2003).

P source and rate (kg/ha)	Season					
	1	2	3	4	5	6
Control	178	375	536	511	281	231
MPR, 13.2	112	550	703	857	321	309
MPR, 26.4	101	558	639	957	358	263
TSP, 13.2	134	415	669	918	319	267
LSD (P = 0.05)	NS	125	NS	NS	NS	NS

semi-arid Tanzania. Groundnut yields were lowest in the first season of MPR and TSP application due to low rainfall, and were highest in the fourth season with treatments increasing the yields which, subsequently declined in the fifth and sixth seasons. Maize yields (not reported here) were also raised by MPR application up to the third cropping season. This shows the positive or residual effect of MPR.

Towards the adoption of soil fertility replenishment technologies

The case studies presented in this paper have demonstrated positive effects of soil fertility management technologies across East African countries, using a wide range of inorganic and organic resources and packages, particularly of low cost materials. Monetary gains resulting from use of various technologies have also been reported. But in spite of demonstrations and appreciation of technologies, Africa is faced with a problem of negligible to nil adoption of technologies in general. The most obvious response is the constraint of expensive agricultural inputs. In one of the attempts to enhance technology adoption, we report preliminary results of field trials that are being conducted in western Kenya under the rare situation of researcher – NGO (Extension) – small farmer co-operation.

In this endeavour, it is recognized that many existing soil fertility management technologies have been developed on an individual or institutional basis and these technologies have rarely been compared side- by-side on their performance. Thus from 2002 (to date) field trials have been installed on 140 smallhold farms across seven districts in western Kenya with varying climate, altitude and soils (Woomer et al. 2003b).

The main objective is to compare the effectiveness and the 'acceptability' of eight soil fertility management options across these farms. One NGO (SACRED Africa) is leading this study with other six NGOs collaborating very closely in the studies. Kenyatta and Moi Universities, Kenya, participate in backstopping (Woomer et al. 2003b).

The guiding principle in the study is the need to compare all existing soil fertility amelioration options side-by-side. It is also believed that farmers will accept profitable options that are labour friendly. In the study, the maize–legume widespread intercropping system was adopted, with farmers managing the trials with the advice of the NGOs. The technologies under test consist of the use of organic and inorganic resources applied individually or in combinations, the use of agroforestry short fallow species and the legume cover crops designed to recycle nutrients and the testing of the newly introduced PREP-PAC and MBILI (staggered two maize and two legume spacing) options. The NGOs selected the farmers who participated and executed all field operations.

Treatments/technologies were:

- The absolute control, representing no nutrient inputs from smallhold farmers.
- Farmers' practice where any form of manure, compost or inorganic fertilizer is applied at varying rates (estimated at 15 kg N + 17 kg P/ha as DAP in Bungoma district, but at 4 t/ha FYM in some districts.
- Organic farming community treatment with biogenic MPR fortified wheat straw or maize stover compost developed at Moi University, Kenya, applied at 2 t/ha (44 kg N + 8.5 kg P/ha).
- PREP-PAC package (as above), this is an input of 100 kg P/ha + 40 kg N/ha urea + Biofix (rhizobial inoculant), also developed at Moi University).
- Mineral fertilizer, the KARI/FURP (1994) treatment consisting of 75 kg N/ha CAN or urea + 20 kg P/ha TSP (or DAP).
- Mineral fertilizer for MBILI package (staggered row intercropping with inputs of 31 kg

Table 15. Soil test data (at preplanting in 2002). Before the installation of Best-Bets Experiment in 7 districts in Western Kenya (means for 20 farms per district).

District	Soil test			
	pH (H_2O)	%C	%N	Olsen P (mg)
Bungoma	5.54	1.37	0.18	4.8
Busia	5.13	1.00	0.27	4.0
Teso	5.73	0.72	0.09	6.6
Trans Nzoia	5.26	2.01	0.27	3.5
Vihiga	4.84	1.23	0.16	3.3
Siaya	4.82	1.67	0.18	3.6
Homa Bay	6.79	2.29	0.43	19.7
Means	(5.44)	(1.47)	(0.23)	(6.5)

Note:
(1) Particularly low available P levels in the soils.
(2) Soils are mainly acrisols, ferralsols (vertisols in Homa Bay) of a sandy to clay texture (in Homa Bay).
(3) Soils are generally acidic and of low organic matter content.

N + 20 kg P/ha (DAP at planting but CAN as a topdressing). MBILI = Managing Beneficial Interactions in Legume Intercrops.

- ICRAF's maize–bean–crotalaria short fallow intercropping system designed to supply upto 200 kg N from the biological nitrogen fixation (BNF) process (fixed by crotalaria), through legume biomass incorporation into soils and nutrient deep root capture.
- Legume cover crop maize cropping, with Lablab (dolichos) incorporated into soils supplying mainly N. No other external inputs were applied to the fallow and to Lablab relay crops.

Maize, beans and groundnut were planted in the first rains 2002 and the same legumes replanted in the second season 2002. Lablab and crotalaria were also planted about mid way in the first season. Details of experimentation and the low carbon, nitrogen and phosphorus status of soils from 140 test farms are described elsewhere (Woomer et al. 2003b). The soil test data for farms at preplanting are given in Table 15 (means for each district). However, being on-farm trials, some failure (23%) in recovery of yield data was met. Thus yield data for crops were obtained in 107 farms (Table 16). The overall performance of the intercropping management showed better performance from four technologies out-yielding the no inputs management. The PREP-PAC produced the highest yields (t/ha/year) and the MBILI package produced the greatest annual net return (ksh./ha/year). This positive effect of MBILI economically is largely due to maize-groundnut intercrop. Groundnut is usually sold for twice the price of beans in most areas of Kenya. Nonetheless, the MBILI management has reduced shading of legumes and an overall yield advantage over conventional intercropping (Woomer et al. 2003b).

Phosphorus use efficiencies by maize from Best-Bets comparison above

Nutrient use efficiency (NUE) by crops is one of the well-known parameters used to evaluate the effectiveness of soil fertility management options. NUE is defined as:

Table 16. Yields (t/ha) of maize and legumes from soil fertility managements (Best Bets) in western Kenya during two cropping seasons of 2002 (the researcher–NGO–farmer co-operation; (after Woomer et al. 2003b).

Soil fertility management	Long rains		Short rains		Cumulative (ksh.)	
	Maize yield	Legume yield	Maize yield	Legume yield	Total costs	Net returns
No inputs	1.95	0.19	0.51	0.14	14515	12036
Farmers practice	2.64	0.22	1.00	0.19	25375	10987
Fortified compost	2.37	0.22	0.92	0.13	18895	13651
Mineral fertilizer	2.72	0.24	1.10	0.15	24584	13238
PREP package	2.78	0.24	1.20	0.08	26185	13336
MBILI package	2.43	0.26	1.26	0.24	20811	25378
Crotalaria fallow[a]	2.06	0.21	n.c.	0.16	14515	9258
Lablab relay	2.03	n.c	0.88	0.14	15412	10388
LSD (0.05) (a)	0.27	0.04	0.27	0.04	551	4150

[a] Crotalaria fallow management was intended to produce next residual benefits.
(a) LSD allows for yield comparison between management and season.
n.c. Shows no yield from the management as no cropping for the component was made in the season in question.

Table 17. Phosphorus use efficiency (kg grain/ kg P uptake) in maize grain from soil fertility management options, combined over five districts in western Kenya, first rains 2002.

District	Technology (treatment)					
	Compost	Farmers' practice	FURP	MBILI	PREP-PAC	Mean
Bungoma	142	116	154	129	226	153
Homa Bay	−168	66	−131	−306	−76	−123
Siaya	235	325	281	323	−17	229
Teso	63	43	177	−264	132	30
Trans Nzoia	67	−46	54	−139	21	−9
Mean	68	101	107	−52	57	56
SED district	66.7					
SED treatment	84.1					
SED dist × trt	157.8					
P dist.	0.123					
P trt.	0.001					
P dist. × trt.	0.206					

Source: Data of K. W. Ndungu and M. N. Kifuko, Best Bets Project Collaborators (unpublished).

$$\text{NUE} = \frac{\text{Change in crop yield above control yield}}{\text{Nutrient uptake by the crop from a nutrient applied}}$$

Thus in the technology comparison for soil fertility management options described above, both N and P inputs varied widely with technologies and therefore the NUEs for these two nutrients are expected to vary. Table 17 presents the P use efficiency data for selected five technologies and districts across western Kenya, focussing the maize grain component (most of the P is accumulated in the grain).

The P use efficiencies varied significantly with soil fertility options across districts, implying differences in maize P uptake from technologies with different P inputs and sites. Negative P use efficiencies are explained in terms of insignificant maize grain yield increases in some districts or soils, like the Homa Bay and Trans Nzoia districts. Homa Bay is particularly associated with rather adequate available P values (Table 15).

Conclusions and recommendations

- Food insecurity in sub-Saharan Africa is mainly explained in terms of low and declining crop yields. But soil fertility depletion particularly contributes to low and unsustained crop yields.
- There is strong evidence that yields can be raised through applications of external nutrient inputs, but specifically the N and P inputs added individually or in combinations. However, in the ASALs, soil moisture stress will limit the uptake of nutrients, implying the need to conserve water and soil organic matter as the top priority.
- Phosphate rocks of varying origins, reactivities and agronomic effectivess are found widely in Africa. Efficient use of these materials needs to be revisited as it reflects a saving on costs associated with importation of refined mineral phosphate fertilizers.
- Towards the adoption process, soil fertility replenishment options should be evaluated side-by-side (or simultaneously) at on-farm level so that the end users and all stakeholders may have an opportunity to give their own assessment and rating of technologies in relation to effectiveness and economic-based information. Preliminary results from this approach in western Kenya need syntheses after experimentation in 2006.
- Extension messages need updating frequently to educate the farmer, particularly on the newly introduced technologies. To this end, short and simple messages in form of brochures are important, as well as other dissemination media.

Acknowledgements

The authors acknowledge the financial support given to them mainly by Kenya Agricultural Research Institute (KARI), Australian Centre for International Agricultural Research (ACIAR) and the Rockefeller Foundation. They are grateful to the Tropical Soil Biology and Fertility (TSBF), Institute of CIAT for invitation to present this paper and their kind funding to attend this symposium. Finally, we wish to thank the Vice Chancellor, Moi University, Eldoret, Kenya for permitting time for the senior author to attend the symposium.

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