Agriculture, Ecosystems & Environment (in press)

Use of deep-rooted tropical pastures to build-up an arable layer through improved soil properties of an Oxisol in the Eastern Plains (Llanos Orientales) of Colombia

E. Amézquita[1], R.J. Thomas[2], I.M. Rao[1], D.L. Molina[1] and P. Hoyos[1]
[1] *Centro Internacional de Agricultura Tropical (CIAT), Apartado Aéreo 6713, Cali, Colombia*
[2] *ICARDA, P.O. BOX 5466, Aleppo, Syria (formerly CIAT, Colombia)*

Abstract

It is widely believed that tropical soils (mainly Oxisols) have excellent physical characteristics such as high infiltration rates, high permeability of water, good and stable soil structure and that consequently, they can support mechanized agriculture. However in the Eastern Plains (Llanos Orientales) of Colombia, when Oxisols are subjected to tillage using disc harrow, soil physical conditions deteriorate rapidly. We report here that change in land use with deep-rooted tropical pastures can enhance soil quality by improving the size and stability of soil aggregates when compared with soils under monocropping. In addition, rates of water infiltration improved by 5 to 10-fold while rainfall acceptance capacity improved by 3 to 5-fold. We suggest that intensive and sustainable use of these Oxisols, could only be possible if an "arable" or "productive layer" (i.e. a layer with improved soil physical, chemical and biological properties) is constructed and maintained. One option to achieve this arable layer is through the use of introduced tropical pastures with deep rooting abilities that can result in increased soil organic matter and associated improvements in soil physical, chemical and biological properties. One land use option that can achieve these soil improvements is agropastoralism whereby pastures and crops are grown in short-term rotations.

Keywords: Soil physical characteristics, Oxisols, Infiltration, Organic matter, Rainfall acceptance, Lower and upper limits of available water

Introduction

Agricultural sustainability implies that agriculture will remain the principal land use over long periods of time relative to human life-span and it is economically competitive and ecologically acceptable while the soil resource base maintains or even improves its fertility and health (Hamblin, 1991). One of the major challenges for the achievement of sustainable agriculture in the tropics, is the vulnerability of tropical soils to degradation when they are subjected to mechanization for crop production (Thomas et al., 1995; Thomas and Ayarza, 1999; Amézquita *et al.,* 2000). It is widely believed that tropical savanna soils (mainly Oxisols) have excellent physical characteristics such as high infiltration rates, high permeability, good and stable soil structure and therefore can support mechanized agriculture (Sanchez and Salinas, 1981). However, recent work indicated that Colombian savanna soils (Oxisols of Altillanura), have serious physical, chemical and biological constraints for crop and pasture production (Amézquita et al., 1998a). Physically the fertile layer can be shallow with high bulk densities together with weak structure. Tillage (disc harrowing) practices currently used for seedbed preparation could result in surface sealing and low rainfall acceptance capacity (Amézquita *et al.,* 2000). Chemically the soils have low pH values, high levels of exchangeable Al^{+3}, low P availability, low base (Ca, Mg and K) saturation and low amounts of organic matter. Also, biologically they show constraints typical of soils with low organic matter such as lower rates of mineralization (Thomas et al., 1995; Lopes *et al.*, 1999).

Physical, chemical and biological conditions of these soils need to be improved in order to increase their productivity. Usually this improvement can be achieved by land preparation and by application of lime and fertilizer. However, this effect lasts only for a short time and after 4 to 7 years, farmers abandon the degraded land as it is no longer productive and often migrate to other areas. To avoid the continued degradation of these soils and to achieve sustained production, we propose that the construction of an “arable layer”, a top layer with improved soil properties, is required (Amézquita *et al.*, 2000).

It has been demonstrated that soil physical conditions are usually best under permanent grassland (or forest) and as soil is cultivated, these conditions deteriorate at a rate dependent of climate, soil texture and management (Lal, 1993; White, 1997). Amézquita *et al*. (1998a), have found significant negative effects of continued cropping on the physical properties of soils in the Llanos. The study by Preciado (1997) from the Casanare region of the Llanos showed that total porosity and macroporosity decrease markedly after 5-7 years of monocropping. Boonman (1997) mentioned similar trends for soils of African savannas.

Ploughing and cultivating new land is usually accompanied by a decline in soil organic matter. When land is ploughed, disruption of peds exposes previously inaccessible organic matter to attack by microorganisms and populations of soil structure-stabilizing fungi and earthworms decrease markedly (White, 1997). Introduced pastures can markedly reverse these trends through improvements in soil aggregation (Drury *et al.*, 1991; Gijsman and Thomas, 1995; Franzluebbers *et al.*, 2000).

The relatively weak structure of savanna soils of Colombia (Oxisols) and their susceptibility to sealing, compaction, and erosion when subjected to tillage can result in negative effects on sustainable productivity of crop-livestock systems (Amézquita, 1998). To overcome these physical constraints, tillage practices should be developed that are based on the concept of development of an “arable layer”. The “arable layer” is a surface layer (0-15, 0-25, 0-30 cm depth), with improved soil physical, chemical and biological properties. This is essential for developing a soil that is capable to support sustainable agriculture (Amézquita *et al.*, 2000).

The “arable layer” concept proposed, is based on the combination of: (1) tillage practices to overcome soil physical constraints (high bulk density, surface sealing, low infiltration rates, poor root penetration, etc.). (2) use of chemical amendments (lime and fertilizers) to enhance soil fertility, and (3) use of soil and crop management practices to increase rooting, to promote biostructure, and to avoid repacking of soil after tillage, thus, improving the biological condition of the soil. This concept relies on the use of deep-rooted and acid soil adapted tropical pastures to improve and maintain soil physical conditions via vertical tillage (chisel).

The purpose of this study was to evaluate the influence of deep-rooted tropical pastures in comparison with other land uses such as monocropping of upland rice and native savanna pastures on the build-up of an arable layer through improved soil properties.

Materials and methods

Location

The experiments were carried out at Matazul farm (4º 9′ 4.9″ N, 72º 38′ 23″ W and 260 m.a.s.l.) located in the Eastern Plains (Llanos) near Puerto López, Colombia. The area has two distinct climatic seasons, a wet season from the beginning of March to December and a dry season from December to March and has an annual average temperature of 26.2 ºC. The area has mean annual rainfall of 2719 mm, potential evapotranspiration of 1623 mm and relative humidity of 81 % (data from the nearby Santa Rosa weather station, located at the Piedmont of the Llanos of Colombia). The soil has low fertility and the availability of P in the soil is low because of the soil’s high P fixation capacity (Phiri et al., 2001).

Treatments

To evaluate the impact of deep-rooted pastures on soil physical characteristics, we used the following treatments from long-term experiments:

a) Aggregate size distribution and aggregate stability aspects were studied in an experiment where disturbed and undisturbed introduced pasture systems were compared with rice monocropping on two sites of contrasting soil texture (Matazul: clay loam; Primavera: sandy loam). Native savanna (undisturbed) system was used as a control. Disturbed pasture received two harrow passes for every two years to reduce surface sealing and compaction.

b) Infiltration rates were measured in an experiment aimed to improve top-soil conditions (cultural profile) using different intensities (1, 2 or 3) of chisel passes (vertical tillage) or different agropastoral treatments (pasture alone, pasture + legume and legumes alone) that were planted after 2 passes of chisel.

c) Measurements on volume and chemical composition of gravitational water were studied in an experiment aimed to understand the processes of soil degradation due to either monocropping of rice or introduced pasture (*Brachiaria dictyoneura* cv. Llanero). Different number of harrow passes (2, 4, 8) were applied every year for a period of two years for each treatment.

d) Root biomass and root volume of *Brachiaria decumbens* were determined in two contrasting textural soils: sandy-loam and clay-loam, under two pasture conditions: productive and degraded (less productive), to compare root growth under these two conditions.

Evaluated Parameters

Aggregate size distribution and aggregate stability

Ten volumetric soil samples were taken in cylinders (120 mm diameter by 25 mm high) and used for dry aggregate size distribution determinations from each of the following treatments: disturbed pasture, undisturbed pasture, monocrop and native savanna. Disturbed pastures means that two harrowing passes were made every 2 years to loosen the soil to improve pasture productivity. By the time of the evaluation, the experimental plots had 8 years of establishment. In each of the 10 samples taken from each treatment, a test for dry aggregate size distribution (Kemper and Rosenau, 1986; White, 1993; Amézquita et al., 1998b) was made using the total volume of soil collected in the cylinders. Sieves of the following openings were used: >6, 6-4, 4-2, 2-1, 1-0.5 mm, which were fitted to a shaker for 5 minutes.

Aggregate stability was determined also using 10 samples (50 g of soil) for each treatment with a Yoder apparatus (Angers and Mehuys, 1993). A set of sieves with openings of: 2, 2-1, 1-0.5, 05-0.25, 0.25-0.125 and <0.125 mm was used. The amount of sand found in each sieve was discounted from the total weight.

Infiltration rate

A double ring devise was used to determine infiltration rates (Bower, 1986). Five tests for each treatment were made. Internal cylinder was inserted into the soil to 5-7 cm soil depth. External cylinder was inserted to 3-5 cm. Water was poured first to the external cylinder to reach a height of about 3 cm within the cylinder and then to the internal cylinder to reach a height of 6 cm from the soil surface. The amount of water entering into the soil was measured at different time intervals during a testing period of two to three hours, until a quasi equilibrium of amount of water entering in function of time was reached.

Collection of gravitational water

It is not common to collect and measure the amount and elemental composition of free water (drainage water) from the precipitation that moves down in a soil profile at different depths. In this study we determined the influence of pastures or monocropping of upland rice on the amount of gravitational water and its elemental composition at different soil depths. A pit of 1.8 m length × 0.7 m wide × 0.5 m depth m was dug in each treatment. Funnels filled with clean fine and very fine sand, were wetted to field capacity and then buried in the soil profile at different depths: 3, 5, 10, 15 and 30 cm to collect the gravitational water that passes through each depth, during part of the rainy season. Measurements of the amount of water and elemental composition, were made at different times. During the period of measurements, the pits were protected around and covered with a sheet of zinc to avoid any other water entering into the pit. This methodology assumes that there is a vertical piston like water movement. The accepted rain was assumed to move through the soil profile and reach the funnels that were buried at different depths. Wet sand present in the funnels favors pore continuity for the drainage process.

Root distribution

Root sampling was carried out using trench profile method (Schuster, 1964). Three sampling points were randomly located within each treatment of degraded or productive pasture of *Brachiaria decumbens*. A trench of 60 cm wide, 50 cm deep and 60 cm long was dug to determine root penetration and root distribution. Root samples were excavated from the wall of each trench, totalling 3 samples from each treatment. The nail-boards were made of a 2 cm thick plywood board (50 cm wide and 40 cm long). Twelve cm long nails were inserted at 10 cm intervals (10 x 10 cm) through the back of the board and protruded into the frame 10 cm.

Root samples were excavated by pressing the nail-boards into the trench wall and slicing the enclosed soil monolith from the trench wall with a steel blade. The samples were soaked in water for at least 2 h after which the soil was removed from the roots with a fine spray of water. The root samples were photographed. Root volume was determined with a measuring jar filled with water by registering the increase in volume. Root biomass (dry weight) was recorded after oven drying for 2 days at 65°C.

Results

Aggregate size distribution and stability

Effect of different management systems.

The aggregate size distribution under different management systems is shown in Table 1. At Matazul Farm, the percentage of aggregates >6 mm, 6–4 mm and 4–2 mm decreased in intervened systems compared with the native savanna, while those between 2–1 mm, 1–0.125 mm and <0.125 mm increased. This was noted particularly under monocropped rice. At La Primavera Farm, monocropping with rice resuted in a lower percentage of 4–2 mm and higher percentage of 2–1 mm and 1.0–0.125 mm aggregates. In contrast, the undisturbed pasture had a positive effect on soil aggregation, with the highest (non-significant) percentage of aggregates larger than 2 mm.

Table 1. Aggregate size distribution (%) as influenced by soil management system in savanna soils of Colombia

	% of aggregates of size (mm)*					
Treatment	>6	6-4	4-2	2-1	1-0.125	<0.125
Matazul Farm						
Undisturbed pasture	14 b	11 b	16 a	15 b	32 b	12 ab
Disturbed pasture	21 a	11 b	15 ab	15 b	27 c	11 b
Rice monocropping	7 c	7 c	13 b	17 a	44 a	13 a
Native savanna	22 a	14 a	16 a	11 c	24 c	10 b
La Primavera Farm						
Undisturbed pasture	14 a	15 a	26 a	17 b	22 b	5 b
Disturbed pasture	6 b	7 c	17 ab	22 a	37 a	11 a
Rice monocropping	13 a	12 b	15 b	18 b	31 a	10 a
Native savanna	11 a	11 b	26 a	18 b	24 b	9 ab

** Values within an aggregate size class and farm followed by the same letter are not significantly different at p<0.05.*

The results on aggregate stability are presented in Table 2. Aggregate stability values at Matazul Farm were greater for native savanna than for intervened systems. The percentage of stable aggregates larger than 2 mm was significantly greater in relation to other treatments. At La Primavera Farm, undisturbed pasture and native savanna both had a higher percentage of aggregates larger than 2 mm diameter.

Table 2. Percentage of stable aggregates under different management systems on a Colombian savanna Oxisol

	% of stable aggregates of size (mm)*					
Treatment	>2	2-1	1-0.5	0.5-0.25	0.25-0.125	<0.125
Matazul Farm						
Undisturbed pasture	75 c	7.2 a	4.0 a	1.6 a	1.6 a	10.0 ab
Disturbed pasture	79 bc	4.5 b	2.7 b	1.2 b	0.9 ab	11.4 a
Rice monocropping	84 b	3.6 b	2.6 b	1.2 b	0.9 ab	7.8 ab
Native savanna	93 a	1.2 c	0.6 c	0.3 c	0.3 b	4.2 b
La Primavera Farm						
Undisturbed pasture	94 a	1.0 c	0.5 c	0.5 b	0.2 b	3.7 b
Disturbed pasture	78 c	7.6 a	3.7 a	1.3 a	1.2 a	8.7 a
Rice monocropping	84 b	4.4 b	2.3 b	0.8 ab	1.0 a	7.8 a
Native savanna	93 a	1.7 c	0.6 c	0.3 b	0.2 b	4.4 b

** Values followed by the same letter are not significantly different at p<0.05.*

Infiltration rates

Infiltration rates, determined under different management system treatments in an experiment aimed to create an arable layer, are shown in Table 3. In relation to native savanna the treatments that included introduced pastures showed higher and more stable rates. Particularly higher rates of infiltration were found under *A. gayanus* pasture.

Table 3. Rate of water infiltration (cm. h^{-1}) as influenced by different treatments in the experiment on building an arable layer (Matazul Farm)

	Infiltration rate (cm h^{-1})	
Treatment	1998	1999
Rice-soybean rotation		
1 chisel pass	2.0 c	5.5 bc
2 chisel passes	1.6 c	7.4 bc
3 chisel passes	2.2 c	7.5 bc
Rice + Pastures		
a) Early incorporation of residues		
A.gayanus (Ag)	17.0 a	15.0 a
Ag+legumes (Kudzu + *D. ovalifolium*)	8.8 abc	5.6 bc
Legumes (Kudzu + *D. ovalifolium*)	9.7 abc	6.8 bc
b) Late incorporation of residues		
A.gayanus (Ag)	8.5 abc	9.4 b
Ag+legumes (Kudzu + *D. ovalifolium*)	6.5 bc	5.2 bc
Legumes (Kudzu + *D. ovalifolium*)	14.2 ab	3.1 c
Native savanna (control)	1.7 c	3.7 bc
Significance level	0.07	0.006

** Values followed by the same letter are not significantly different at p<0.05.*

Gravitational water

The amount of gravitational water draining at different soil depths as a function of soil management system is shown in Table 4. Little water was collected in the top layers of soil of savanna while greater amounts were collected at 15 cm soil depth. The treatment sown to upland rice with 8 harrow passes, did not allow the movement of free water through the soil. With 16 harrow passes more water was able to enter into the soil especially in the top two layers.

Under introduced pastures, the amount of free water entering and moving through the soil profile was extremely high (480 cm^3 vs 0 cm^3 with 8 harrow passes and 490 cm^3 vs 100 cm^3 with 16 harrow passes) in comparison with upland rice.

The chemical composition of the water collected at different soil depths under upland rice and pastures is shown in Table 5. Higher amounts of nutrients, especially at the first two depths were found under rice.

Root distribution

Examination of soil monoliths collected through profile wall technique showed marked differences in root penetration and root distribution between a degraded pasture and a productive pasture of *Brachiaria decumbens* (Figure 1). Differences in root biomass and root volume at different soil depths, as influenced by soil texture (clay-loam and sandy-loam) are shown in Table 6. Clearly the productive pasture showed greater abundance and distribution of root systems than the degraded one.

Discussion

Good soil management should aim to create optimum physical conditions for plant growth (White, 1977). These include: a) adequate aeration for roots and microorganisms. b) adequate available water, c) easy root penetration, d) rapid and uniform seed germination, and e) resistance of the soil to slaking, surface sealing and accelerated erosion. Results from this study indicate that change in land use as deep-rooted tropical pasture can enhance soil quality by improving the size distribution of stable aggregates when compared with soils under continuous upland rice monocropping. The greater percentage of stable aggregates with introduced pastures compared with monocropping indicates that any kind of soil disturbance negatively affects aggregate stability, possibly through its influence on soil organic matter (Hamblin, 1985; Lal, 1993) or some of its components (Caron *et al.*, 1992). Compared with native savanna, introduced pastures also showed higher and more stable rates of water infiltration, particularly with *A. gayanus* pasture. These results reconfirm the benefits of introduced pastures in improving soil quality (CIAT, 1998; Gijsman and Thomas, 1996).

The improvement of the structural condition of soils by pastures, when they are used for grazing, normally change to less beneficial values of porosity, infiltrability, etc., as a consequence of trampling. However, strategies to maintain a good soil structural quality can be developed with proper grazing management.

Little amount of gravitational water was collected in the top layers of soil of native savanna while greater amounts were collected at 15 cm soil depth suggesting the existence of preferential flow. This could be due to the wetting mechanisms dominant in the natural savannas. The treatment sown to upland rice with 8 harrow passes, did not allow the movement of free water through the soil, probably as a result of surface sealing that impeded the entrance of water. Under 16 harrow passes more water was able to enter into the soil especially in the first two depths, showing that there was a better rainfall acceptance under this treatment. The greater amounts of gravitational water entering and moving through the soil profile of introduced pasture in comparison with monocropping of upland rice indicates that introduced pastures are a very good alternative to improve and maintain the amount of macropores (pores that permit the free movement of water). This result confirms the beneficial effects of agropastoral system for improvement of these soils (Angers, 1992). Results on the chemical composition of the gravitational water collected indicate the beneficial effects of introduced pastures both on water and nutrient redistribution in the top-soil layers. However, it is important to note that pastures were sown a year before rice. `

Table 4. Gravitational water collected (ml) at different soil depths for different systems of soil management (Matazul Farm)

Depth (cm)	Amount of water collected (ml)				
		Rice		Pasture	
	Native savanna	8 harrow passes	16 harrow passes	8 harrow passes	16 harrow passes
3	3	0	100	480	490
5	2	0	136	480	490
10	4	1	0	480	447
15	490	2	0	440	132
20	1	0	0	40	78
30	0	3	0	0	460

Table 5. Elemental composition of gravitational water collected at different depths and management systems (Matazul Farm)'

Crop	Depth (cm)	N	K	Ca	Mg	Al	Electrical conductivity ($\mu S\ cm^{-1}$)	pH
		($mg\ L^{-1}$)						
Rice	3	8.5	12.0	2.9	0.5	6.0	103.8	5.8
	5	2.8	10.4	6.0	1.0	17.5	90.0	6.0
	3	1.7	4.1	1.7	0.5	2.2	463.0	5.9
	5	2.9	0.6	1.6	0.3	1.4	29.5	6.2
Pastures	10	2.0	1.4	0.8	0.2	0.4	288.0	6.1
	15	2.0	2.6	2.8	0.4	0.6	47.5	6.6
	20	2.7	1.5	2.3	0.4	0.5	56.3	6.7
	30	4.8	3.8	3.7	1.0	1.7	79.0	6.6

Table 6. Root biomass (g) and root volume (cm^3) of *Brachiaria decumbens* at different soil depths as influenced by level of pasture productivity (degraded or productive) on two soil types.

Soil depth	Sandy-loam			Clay-loam		
(cm)	Degraded	Productive	$LSD_{0.05}$	Degraded	Productive	$LSD_{0.05}$
Root biomass (g)						
0-15	0.7	1.3	0.64	1.0	1.7	NS
15-25	0.2	0.2	NS	0.3	0.3	NS
25-40	0.1	0.3	0.08	0.2	0.2	NS
Root volume (cm^3)						
0-5	6.5	9.7	NS	8.5	15.7	5.6
15-25	2.2	2.7	NS	2.7	2.6	NS
25-40	1.2	2.7	0.8	2.1	2.1	NS

Degraded Productive

Figure 1. Root distribution under degraded and productive *Brachiaria decumbens* pasture.

Four aspects of the research deserve to be emphasized. First, the methodology used was appropriate as it was possible to collect drainage water and differentiate between treatments. Second, there was a very high variability in the way the water moved into the soil (preferential flow). Third, the amount of nutrients that moved from one depth to the other was a function of the total amount of water draining through soil profile. Fourth, the greater capacity of the pastures for facilitating a better movement and distribution of nutrients and water could be used for improving soil physical conditions.

Conclusions

This study shows that change in land use as introduced pastures can enhance soil quality by improving the size distribution of stable aggregates, water infiltration rates and rainfall acceptance capacity when compared with soils under monocropping. We suggest that the intensive and sustainable use of these soils, is only possible if an "arable" or "productive layer" is produced and maintained i.e. a layer with little physical, chemical and biological constraints. One option to achieve this arable layer is the use of introduced pastures with deep rooting abilities that can result in increased soil organic matter and associated improvements in soil physical and chemical properties. One land management option that can achieve these improvements is agropastoralism whereby pastures and crops are grown in short-term rotations.

Acknowledgements

We are grateful to COLCIENCIAS (Instituto Colombiano para el Desarrollo de la Ciencia y la Tecnología "Francisco José de Caldas", Colombia) for their financial support to field studies in the Llanos of Colombia.

References

Amézquita, E., I.M. Rao, D.L. Molina, S. Phiri, R. Lal and R.J. Thomas. 2000. Constructing an arable layer: key issue for sustainable agriculture in tropical savanna soils, Paper presented at ISCO conference. Fort Worth, Texas. USA. July, 2000.

Amézquita, E., G. Preciado, D.M. Arias, R.J. Thomas, D.K. Friesen, J.I. Sanz. 1998a. Soil physical characteristics under different land use systems and duration on the Colombian savannas. 16th World Congress of Soil Science. Montpellier, France (Poster presentation).

Amézquita , E., E. Barrios, I.M. Rao, R.J. Thomas, J.I. Sanz, P. Hoyos, D.L. Molina, L.F. Chávez, A. Alvarez, J.H. Galvis. 1998b. Improvement of some soil physical conditions through tillage. pp.57-

59. CIAT PE-2 Annual Report 1998. CIAT, Cali, Colombia.
Amézquita, E. 1998. Hacia la sostenibilidad de los suelos de los Llanos Orientales. pp.106-120. *In*: Memorias "Manejo de Suelos e Impacto Ambiental" IX Congreso Colombiano de la Ciencia del Suelo, Paipa, Octubre 21-24 de 1998. Sociedad Colombiana de la Ciencia del Suelo, Bogotá, Colombia.
Angers, D.A. 1992. Changes in soil aggregation and organic carbon under corn and alfalfa. Soil Sci. Soc. Am. J. 56:1244-1249.
Boonman, J.G. 1997. Farmers' Success with Tropical Grasses: Crop-pasture rotations in mixed farming in East Africa. Netherlands Development Assistance (NEDA), Information Department, Ministry of Foreign Affairs, The Hague, Netherlands. 96 p.
Bower, H. 1986. Intake rate: cylinder infiltrometer. In, A.Klute ed. 1986. Methods of soil analysis. Part 1. Am.Soc.Agron.Soil Scie.Soc. Amer. Madison, Wisconsin, USA. pp.825-843.
Caron, J., B.D. Kay and E. Perfect. 1992.. Short-term decrease in soil structural stability following bromegrass establishment on a clay loam. Soil Tillage Res. 25:167-185.
CIAT (Centro Internacional de Agricultura Tropical). 1998. Annual Report 1998. PE-2 Overcoming Soil Degradation. 81 p.
Drury, C.F., J.A. Stone, and W.I. Findlay. 1991. Microbial biomass and soil structure associated with corn, grasses, and legumes. Soil Sci. Soc. Am. J. 55:805-811.
Franzluebbers, A.J., S.F. Wright and J.A. Stuedemann. 2000. Soil aggregation and glomalin under pastures in the Southern Piedmont USA. Soil Sci. Soc. Am. J. 64:1018-1026.
Hamblin, A.P. 1985. The influence of soil structure on water movement, crop root growth, and water uptake. Advances in Agronomy 38:95-158.
Hamblin, A.P. 1991. Sustainable Agricultural Systems: what are the appropriate measures for soil structure? Aust.J. Soil Res. 29:709-715.
Gijsman, A.J. and R.J. Thomas. 1995. Aggregate size distribution and stability of an Oxisol under legume-based and pure grass pastures in the Eastern Colombian savannas. Aust. J. Soil Res. 33:153-165.
Gijsman, A.J. and R.J. Thomas. 1996. Evaluation of some physical properties of an oxisol after conversion of native savanna into legume-based or pure grass pastures. Trop. Grassl. 30:237-248.
Kemper, W.D. and R.C. Rosenau. 1986. Aggregate stability and size distribution. *In:* Methods of Soil Analysis. ASA. pp.425-442.
Lal, R. 1993. Tillage effects on soil degradation, soil resilience, soil quality and sustainability. Soil Tillage Res. 27:1-8.
Lopes, A., M.A. Ayarza, and R.J. Thomas. 1999. Sistemas agropastoriles en las sabanas de América Latina tropical: lecciones del desarrollo agrícola de los Cerrados de Brasil. *In:* E.P. Guimarães, J.I. Sanz, I.M. Rao, M.C. Amézquita, E. Amézquita, eds. Sistemas Agropastoriles en Sabanas Tropicales de América Latina. CIAT/EMBRAPA. pp.9-30.
Phiri, S., E. Amezquita, I.M.Rao, and B.R. Singh. 2001. Disc harrowing intensity and its impact on soil properties and plant growth of agropastoral systems in the Llanos of Colombia. Soil Tillage Res. 62:131-143.
Preciado, L.G. 1997. Influencia del tiempo de uso del suelo en las propiedades físicas, en la productividad y sostenibilidad del cultivo de arroz en Casanare. Tesis de Maestría. Universidad Nacional de Colombia, Sede Palmira. 111 p.
Sanchez, P. and J.G. Salinas. 1981. Low-input technology for managing Oxisols and Ultisols in tropical America. Adv. Agron. 34:280-406.
Schuster, J.L. 1964. Root development of native plants under three grazing intensities. Ecology 45: 63-70.
Thomas, R.J. and M.A. Ayarza. 1999. Sustainable land management for the Oxisols of the Latin American savannas: dynamics of soil organic matter and indicators of soil quality. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia. 231 p.
Thomas, R.J., M.J. Fisher, M.A. Ayarza, J.I. Sanz. 1995. The role of forage grasses and legumes in maintaining the productivity of acid soils in Latin America. pp.61-83. *In:* R. Lal, J.B. Stewart, eds. Soil Management: Experimental Basis for Sustainability and Environmental Quality. Adv. Soil Sci. Series. Lewis Publishers, Boca Raton, USA.
White, R.E. 1997. Principles and practice of soil science. The soil as a natural resource. Blackwell Science, United Kingdom. 3rd Edition. 348 p.

Paper presented at the 17th World Congress of Soil Science, Bangkok, Thailand, 14-21, August 2002
Comission: 1

Sustainability of Crop Rotation and Ley Pasture Systems on the Acid-Soil Savannas of South America

E. Amézquita[1], D.K. Friesen[2], M. Rivera[1], I.M. Rao[1], E. Barrios[1], J.J. Jiménez[1], T. Decaëns [3] and R.J. Thomas[4]

[1]*Centro Internacional de Agricultura Tropical (CIAT), A.A. 6713, Cali, Colombia.*
[2]*IFDC-CIMMYT, P.O. Box 25171, Nairobi, Kenya (formerly IFDC/CIAT).*
[3]*Université de Rouen, F-76821 Mt Saint Aignan Cedex, France.*
[4]*ICARDA, P.O. Box 5466, Aleppo, Syria (formerly CIAT, Colombia).*

Abstract

Intensification of agricultural production on the acid-soil savannas of south America (mainly Oxisols) is constrained by the lack of diversity in acid (aluminum) tolerant crop germplasm, poor soil fertility and high vulnerability to soil physical, chemical and biological degradation. The use of high levels of inputs and monocropping is thought to be unsustainable since it may result in deterioration of soil physical properties as well as escalation of pest and disease problems. Traditional grazing systems on native savanna species have very low productivity. Improved legume-based pastures can actually improve the soil resource base but require investments in inputs for establishment, which are unattractive to graziers. Other alternatives include establishment of pastures in association with rice (agropastoral systems) as well as rotations with grain legumes or green manures. Systems such as these may attenuate or reverse the deleterious effects of monocultures while permitting intensified agricultural production. To monitor the sustainability of such systems, biophysical measures are required as 'predictors' of system performance and 'health'. In 1993, a long-term field experiment was established in Carimagua, Colombia, (4°36'N, 71°19'W) to study the influence of various systems on soil quality and system productivity on a savanna Oxisol. Soil biophysical properties were measured in potentially degrading and non-degrading production systems. In this paper, we report results obtained during the first five-years of experimentation on the impact of these diverse systems (rice monoculture, rice–cowpea rotation, rice–green manure rotation, rice–agropastoral rotation and native savanna) on soil quality and rice production. Increasing intensity of production system (with concomitant use of inputs) resulted in improved indicators of soil fertility. Cultivation resulted in improved soil physical characteristics, primarily because of the degraded nature of the soil under native savanna. In contrast, soil organic matter declined with increasing intensity of cultivation as did populations of macrofauna in the different systems. Only in the agropastoral system were soil organic matter and macrofaunal activity enhanced. This study provides important indicators for resource management on savanna Oxisols.

Keywords: agro-pastoral systems, crop rotation, soil degradation, soil improvement, soil physical vulnerability, tropical savanna

Introduction

The neotropical savannas occupy 243 million hectares in South America and are one of the most rapidly expanding agricultural frontiers in the world (Thomas and Ayarza, 1999). Oxisols predominate in the hyperisothermic savannas and cover an area of 17 million hectares in Colombia alone. Intensification of agricultural production in this ecosystem requires acid soil (aluminum) tolerant crop germplasm, soil fertility improvement and management of highly vulnerable physical properties (Amézquita, 1998; Guimaraes et al., 1999). Monocropping systems with high levels of inputs and excessive cultivation may be unsustainable since they may cause deterioration of soil physical properties as well as escalation of pest and disease problems.

Improved legume-based pastures are considered least harmful to the soil resource base but require investments in inputs for establishment that are unattractive or beyond the means of graziers. Establishment of pastures in association with rice (to defray the cost of inputs) is a potential alternative that has seen significant adoption by farmers in frontier areas of the Colombian Llanos (Sanz et al., 1999). Alternative systems incorporating components that attenuate or reverse the deleterious effects of monocultures are required, and biophysical measures of sustainability need to be developed as 'predictors' of system 'health' to sustain agricultural production at high levels while minimizing soil degradation.

Grain legumes, green manures, intercrops and leys are possible system components that could increase the stability of systems involving annual crops (Karlen et al., 1994). To test the effects of these components on system sustainability and to identify indicators of soil quality, a long-term field study was implemented in 1993 on a Colombian Oxisol under native savanna grassland using a selection of alternatives based on these components (Friesen et al., 1997). The study has extended through almost two cycles of the principal rotation, i.e., the agropastoral system, recognizing that the degrading or beneficial effects of various agricultural practices are often subtle and only manifest themselves over long periods. This paper presents results from the initial 5-year phase of the experiment, focusing on systems based on upland rice with emphasis on systems' effects on: (a) productivity; (b) soil fertility indicators; (c) soil physical attributes; (d) associated soil organic matter quality; and (d) soil biological health.

Materials and Methods

Site description and experimental design

The experiment was established on a well-drained silt clay loam (Tropeptic Haplustox, isohyperthermic) under native savanna grassland at Carimagua (4°37'N, 71°19'W, 175 m altitude) in the Eastern Plains of Colombia. The mean annual rainfall is 2240 mm with a mean temperature of 27°C. The experiment is laid out in a split-plot design with four replications in which alternative systems (in sub-plots, size 0.36 ha) based on upland rice or maize (main plots) are compared (Friesen et al., 1997). Only rice-based systems are reported here. They include rice monoculture, rice rotated with cowpeas (for grain), cowpea green manure (GM) or "improved" grass-legume pasture leys. Cowpea or GM rotations occurred within each year, i.e., rice was sown in the first season (semester) and the legumes in the second season annually. Pastures were sown simultaneously under rice in 1993 and again in 1998, and grazed in the intervening 4 years. Native savanna plots were maintained for baseline comparisons. Cropped systems were limed with 500 kg ha^{-1} of dolomite prior to establishment and maintained thereafter with annual applications of 200 kg ha^{-1}. Each rice crop received 80 kg-N ha^{-1} (split: 20+30+30), 60 kg-P ha^{-1} and 100 kg-K ha^{-1}. Legumes (cowpeas or GM) received 20 kg-N ha^{-1}, 40 kg-P ha^{-1} and 60 kg-K ha^{-1}. Pastures were fertilized biennially with 20 kg-P ha^{-1}. Plot sizes of 200 m × 18 m (3600 m^2) were used to allow for grazing by cattle and the use of conventional machinery which impact directly on soil physical properties especially. A description of treatments is provided in Table 1.

Soil and plant sampling and analytical procedures

Soils were sampled before planting rice each year from different systems including native savanna. The samples were air-dried, and visible plant roots were removed before they were gently crushed to pass a 2-mm sieve. The following chemical analyses were carried out: pH (1:1 soil:H_2O ratio), exchangeable Al and Ca extracted in 1M KCl, and available P by the Bray-2 method. Soil pore-size distribution was determined from the moisture characteristic curves using undisturbed soil cores (50 mm × 25 mm) taken from the 0-10, 10-20 and 20-40 cm soil layers of each replicate (Phiri et al., 2001). Saturated soil cores were weighed and then subjected to different tensions (5, 10, 100, 300 and 1500 kPa). Pore-size distribution was calculated using the Kelvin equation. Pores were divided into macropores (>50 μm; drained at a tension of ≤6 kPa), mesopores (50-0.2 μm; water retained at >6 kPa but <1500 kPa) and micropores (<0.2 μm; water retained at >1500 kPa).

Table 1. Treatment description: First agropastoral cycle (five years).

Treatment No.	System	Description
1	Native savanna	Managed traditionally by burning annually during dry season; not grazed.
2	Rice-agropastoral rotation	*Brachiaria humidicola / Centrosema acutifolium / Stylosanthes capitata / Arachis pintoi* cocktail sown with rice in year-1 and 6; grazed to maintain legume content.
3	Rice monoculture	Rice grown in monoculture; one crop per year in the first semester; second semester weedy fallow turned in with early land preparation at end of rainy season.
4	Rice-cowpea (grain) rotation	Rice (1st semester) and cowpea (2nd semester) in 1-year rotation; residues incorporated prior to planting in following season.
5	Rice-cowpea (green manure) rotation	Rice (1st semester) and green manure (2nd semester) in 1-year rotation. Legumes incorporated at maximum standing biomass levels in late rainy season.

Soil organic matter quality

Soil samples were taken for the 0-10 cm and 10-20 cm layers of each treatment in February 1998 in order to characterize the impact of production system on soil organic matter quantity and quality. Total soil C and N were determined by combustion on a Leco CHN analyzer and C:N ratio calculated. Size- density fractionation of soil organic matter (SOM) was done using the Ludox Method to separate three size-density fractions: LL (>150 µm, <1.13 g cm^{-3}), LM (>150 µm, 1.13-1.37 g cm^{-3}) and LH (>150 µm, >1.37 g cm^{-3}) identified as most promising by Barrios et al. (1996).

Earthworm populations under different systems

In June 1994 and June 1996 (rainy season), the earthworm community, comprising eight species native to the savanna ecology, were sampled by taking 25×25×30 cm soil monoliths at 50 to 120 points on a regular grid in each plot of each system. Samples were taken quickly, sorted and earthworm species identified and counted at each point. Earthworm biomass was estimated using available data of mean weights of each species at the period of sampling (Decaëns and Jiménez, 2002).

System productivity

Rice grain yields were measured each year in at least four 5m × 5m quadrats located randomly in each plot prior to harvesting the rice crop with a combine harvester. Grain, straw and weeds were separated, weighed and subsampled for moisture content and chemical analysis.

Results

Impact of systems on soil fertility indicators

Soil chemical characteristics under the different systems is shown in Figure 1 where systems are arranged from left to right in order of increasing intensity of input use and cultivation. Temporal changes in soil pH and exchangeable Al were very similar in all systems, with the exception of the inexplicably high Al values in the surface soil under pasture in the later years. The temporal fluctuations in soil pH and exchangeable Al observed in all soil layers can probably be attributed to variability associated with factors such as burning and temporary anaerobic conditions due to high rainfall which directly impact on soil pH and, consequently, soluble Al.

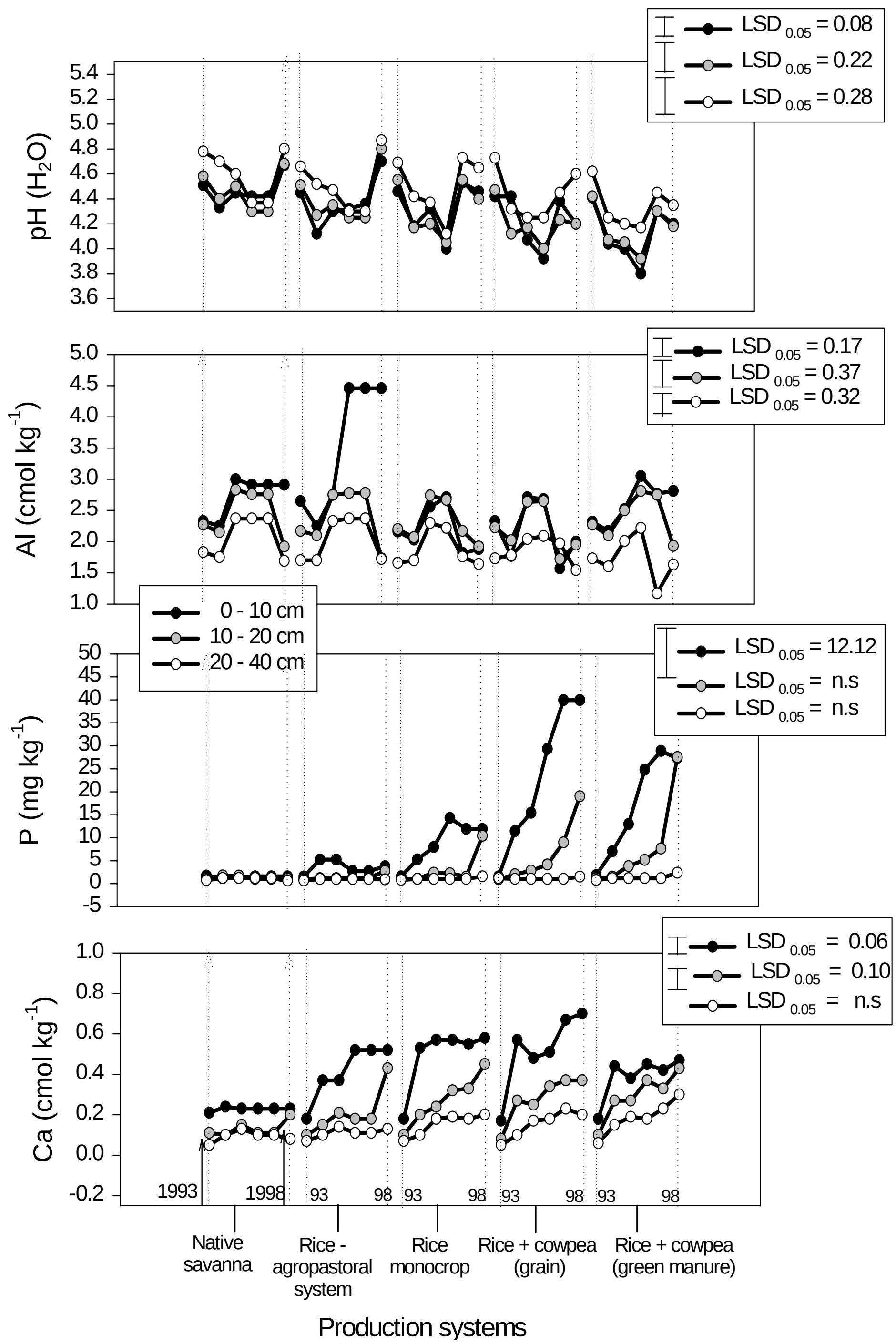


Figure 1. Changes in soil chemical characteristics under different rice-based production systems during five years (1993-98).

Soil fertility indicators for P and Ca generally reflected increasing system intensity. In the absence of inputs to the native savanna system, no significant changes in available P or exchangeable Ca were observed during the five years of experimentation. P availability remained at low levels at all depths (0-10, 10-20 and 20-40 cm), and exchangeable Ca was higher in the surface soil (0-10 cm) than in subsoil layers. Under the rice-agropastoral system, available P and exchangeable Ca levels increased modestly with time in response to the initial applications of lime and P to the pioneer rice crop and the small biennial maintenance applications to the pasture thereafter. The resultant levels of available P (about 10 mg kg^{-1}) are considered adequate for acid soil adapted forage germplasm.

Under rice-monocrop system, P availability increased during the first three years in response to P fertilization but failed to reflect P additions in the latter two years, especially in the surface soil layer (0-10 cm). This could be due to P removal by weeds which became increasingly prevalent as the experiment progressed, and to P fixation by soil incorporated from subsoil layers through excessive ploughing (Friesen et al., 1997). The increase in available P in the 10-20 cm layer in 1998 supports this interpretation. Exchangeable Ca increased in all soil layers in response to annual lime applications. In the surface soil, the largest increase occurred in the first year and remained unvarying thereafter. Instead, annual Ca inputs were reflected in the 10-20 and 20-40 cm layers which progressively increased during the 5-year period, presumably due to leaching from the surface soil.

Changes in soil pH and exchangeable Al were not well correlated with exchangeable Ca, contrary to expectations, probably due to the very low lime rates applied and Ca leaching as a neutral cation with nitrate or chloride which would not affect pH. Changes in exchangeable Ca under the rice-cowpea rotation were very similar to those under rice monoculture although movement of Ca into the subsoil was slightly less, perhaps due to scavenging by deep cowpea roots and cycling of Ca back to the surface through cowpea residues. In contrast, levels of available P in the 0-10 cm layer increased much more sharply over time and were accompanied by increased levels of available P in the subsurface 10-20 cm layer. These increases in available P reflect the additional applications of P fertilizer to cowpea component of the rotation while subsoil increases were probably the result of the increased frequency of cultivation required for the cowpea crop.

The rice-GM system was the most intensely cultivated. Although inputs of lime and P fertilizer were the same as for the rice-cowpea system, there were some notable differences in available P and exchangeable Ca dynamics between the two. Exchangeable Ca in the 0-10 cm layer did not rise to the levels observed in either the rice monoculture or the rice-cowpea system, although changes in the subsoil layers were very similar. This can be explained by an increased rate of leaching of soluble Ca through the soil profile with the much higher nitrate concentrations generated by mineralization of ammonia produced by decomposing GM residues (Friesen et al., 1998). Available P followed a similar temporal trend to that observed in the rice-cowpea system in the first three years. However, in the latter two years, the increased intensity of tillage apparently caused some incorporation of P into the subsoil layer, resulting in a reduced level of available P in the surface soil and an increased level in the subsoil.

Impact on soil physical characteristics

The impact of the different crop rotation and ley pasture systems on some soil physical characteristics 5-years after establishment is shown in Table 2. In general, the saturated hydraulic conductivity of this Oxisol under native savanna is low in the surface soil and even lower in the subsoil layers. A hydraulic conductivity of 10 cm h^{-1} would be considered critical for the prevailing climatic conditions at Carimagua (2700 mm $year^{-1}$ rainfall with high intensity 100-120 mm h^{-1} of rain storms). Most of the observed values were below this critical value. These results indicate that this soil has limited ability for downward movement of water, resulting in temporary waterlogging during intense storms. Infiltration of water through the soil profile is more critical with depth. Thus, any soil management strategy must include improvement of soil hydraulic conductivity. The various rice-based systems had no significant impact on hydraulic conductivity of the surface soil layer after 5 years of tillage at increasing levels of intensity. Measured two years later, chisel ploughing to 30 cm in the annual rotations and monoculture systems caused increased hydraulic conductivity in the 10-20 cm layer but not the 20-40 cm layer. Rooting of cowpeas in the subsoil apparently aided in maintaining the effects of chiseling more than rice alone.

Table 2. Impact of different crop rotation and ley farming systems on certain soil physical characteristics at 5 years after establishment of the experiment.

Depth (cm)	Treatment	Hydraulic conductivity ($cm\ h^{-1}$)	Bulk density ($g\ cm^{-3}$)	Macroporosity (%)
0-10	Native savanna	5.1	1.24	14.6
	Rice–Agropastoral	3.9	1.31	12.3
	Rice monoculture	5.3	1.17	19.6
	Rice–cowpea	7.4	1.29	14.6
	Rice–GM	6.1	1.19	14.4
	$LSD_{0.05}$	NS	0.09	5.1
10-20	Native savanna	0.9	1.31	11.3
	Rice–Agropastoral	0.5	1.37	7.8
	Rice monoculture	5.9	1.23	15.9
	Rice–cowpea	14.4	1.23	17.1
	Rice–GM	13.5	1.25	17.2
	$LSD_{0.05}$	11.4	0.09	5.3
20-40	Native savanna	0.4	1.42	7.2
	Rice–Agropastoral	3.0	1.35	11.0
	Rice monoculture	0.8	1.47	6.5
	Rice–cowpea	1.9	1.34	11.3
	Rice–GM	3.7	1.31	12.4
	$LSD_{0.05}$	NS	0.12	5.2

GM = cowpea green manure.

Statistically significant differences were found in bulk density among systems at different depths but the values found for 0-10 and 10-20 cm soil layers could be considered non-limiting for root growth and distribution. Below 20 cm soil depth where tillage implements (disc harrows) used for land preparation are not expected to have any direct impact, bulk density values were generally higher than those found in the ploughed layers. However, they were not substantially different than native savanna at that depth, indicating that land preparation was not causing added compaction in subsoil layers.

Although some statistically significant differences in macroporosity were found among the different systems, values in the 0-10 and 10-20 cm soil layers are considered non-limiting for root growth and distribution. Below this depth, some values lower than the critical level (10%) were observed. Monocropping of rice resulted in marked decrease of macroporosity for 20-40 cm soil depth when compared with rotation systems.

Impact on soil organic matter fractions

Trends among systems in total soil organic C and SOM fractions (i.e., LL-C) were generally the same (Table 3). However, SOM fractions were more sensitive to the effects of production system than conventional measures of total soil C. LL-C content revealed greater differences among treatments at 0-10 cm soil depth and also found significant effects at 10-20 cm depth. This agrees with results of Barrios et al. (1996, 1997) where the LL-C fraction was identified as a sensitive indicator of SOM changes due to soil and crop management not detected by total soil C.

Surface soil (0-10 cm) LL-C was usually higher than that of the sub-soil. Both total C and LL-C were highest in the agropastoral system and became progressively lower in the annual rice-based systems, in step with increasing intensity of cultivation in the order:

Rice monocrop (1 cultivation yr^{-1}) > rice-cowpea (2 yr^{-1}) > rice-GM (3 yr^{-1})

Despite the large quantities of crop and GM residues incorporated into these systems, only the agropastoral system succeeded in building total SOM content; all other systems experienced declining total C values. Only the rice-GM system showed an increase in LL-C at 10-20 cm depth.

Table 3. Soil total C, light SOM fraction C (LL-C) and C:N ratio in surface and sub-soil layers of rice-based systems.

Treatment	Total soil C		*LL-C fraction*		C:N ratio	
	0-10 cm	10-20 cm	0-10 cm	10-20 cm	0-10 cm	10-20 cm
Native savanna	23950 ab*	18200 a	595 b	217 ab	15.8 b	17.0 a
Rice–agropastoral	25450 a	18925 a	794 a	239 ab	18.9 a	18.1 a
Rice monocrop	22450 bc	19975 a	497 bc	167 bc	16.4 b	17.2 a
Rice–cowpea	22700 bc	18725 a	419 c	101 c	16.4 b	17.5 a
Rice–GM	21075 d	21050 a	301 d	335 a	13.8 c	17.1 a

*Within columns, means followed by the same letter are not significantly different according to LSD (0.05).

Soil C:N ratio was significantly reduced in the surface soil of the rice-GM system, corresponding to the inputs of high quality organic residues. On the other hand, C:N ratio increased significantly in the agropastoral system, probably due to the high litter production of the grass component with its high C:N ratio. Lower soil C:N ratios in the rice-GM system are indicative of higher potential soil N availability, which can be equated with improved plant nutrition or alternatively greater potential for N loss from the system. High rates of legume residue decomposition in this experiment were reported previously (Friesen et al, 1998) and explain the failure to generate an increased SOM content in this system despite the high organic matter inputs.

Impact of systems on soil macrofauna (earthworms)

Intensification and land use system affected earthworm communities in different ways. One year after breaking native savanna (1993), a drastic reduction in earthworm density and biomass was observed in the established rice monocrop and agropastoral systems. Two years later (1996), earthworm density and biomass decreased sharply along a gradient in which highly intensified annual crop systems had deep detrimental impacts that were more accentuated in the rotations (i.e. systems that were tilled 2 or 3 time per year) – down to 3 individuals m^{-2} and 0.1 g m^{-2} in the rice-GM rotation from 50 individuals m^{-2} and 3.2 g m^{-2} in the native savanna (Decaëns and Jiménez, 2002).

Earthworm species responded differently to intensification. Only one species, the small endogeic *Ocnerodrilidae* sp., seemed to be enhanced by the conversion of the savanna into annual crops which usually led to a drastic reduction of the number of species. Three species, *Andiodrilus* n. sp., *Aymara* n. sp. and *Glossodrilus* n. sp. often disappeared from the soil of these systems (Decaëns and Jiménez, 2002), although those species with a high surface mobility were able to colonize the agroecosystems again. Other species showed a high population growth potential that allowed them to recover to their population density before the perturbation. Sensitive species disappeared after pasture establishment but richness was recovered 3 years later.

Impact of systems on rice productivity

Average rice grain yields fluctuated from year to year in response to differences in moisture availability and, more importantly, increased competition from weeds (data not shown). The latter also resulted in increased variability and an inability to detect significant differences among systems in later years (Table 4). Rice-legume (cowpea or GM) rotations tended to produce greater yields throughout the 4-year period following establishment in 1993; however, these were only statistically significant in 1994.

With the exception of 1995, average rice grain yields did not show any apparent decline with time in any of the three annual production systems.

Table 4. Grain yields of upland rice from different rice-based systems.

Treatment	1993§	1994	1995	1996	1997
	------------------------ (Mg grain ha^{-1}) ------------------------				
Rice–agropastoral	3290b*	-	-	-	-
Rice monoculture	2820a	2120a	1280	3220	3090
Rice–cowpea rotation	2820a	3210b	1380	2520	5070
Rice–GM rotation	2820a	3380b	2140	3230	5430
Level of significance	0.02	0.01	0.27	0.28	0.24
CV (%)	6	12	46	22	39

§ rice yields in monoculture and rotations measured as one plot in Year 1.
*Within columns, means followed by the same letter are not significantly different according to LSD (0.05).

Discussion and Conclusions

This 5-year field study examined the effects of contrasting rice-based production systems on rice productivity and indicators of soil chemical/fertility, physical and biological health. Increased intensity of fertilizer inputs associated with increased system intensity generally resulted in commensurate increases in soil fertility under those systems. A previous report (Friesen et al, 1998) showed increasing levels of inorganic N in soil profiles to 1-m depth under rice monoculture < rice-cowpea < rice-GM, with significant and substantial leaching due primarily to legume residues in the latter two systems. The long-term consequences and externalities of improved N fertility in such systems cannot be discounted.

Soil physical characteristics were generally improved with increasing system intensity, probably due to the degraded nature of the soils under native savanna. Cultivation generally helped to create an ‘arable layer’ (Phiri et al, 2001) by incorporating immobile nutrients such as P to depth in this infertile Oxisol. However, these beneficial effects can only be considered short-term. Cultivation also resulted in declining levels of SOM, particularly in the LL-C fraction, which may have consequences on soil structure in the longer term.

Soil macrofauna were the most adversely affected by production systems. Cultivation caused drastic reductions in earthworm populations and biomass, more severely so with increasing intensity and frequency. Since soil macrofauna have direct beneficial effects on many soil characteristics that affect its long term productivity (such as nutrient cycling, soil structure, soil water dynamics, bulk density and root penetrability), managing systems in ways that minimize the impact on macrofaunal populations will be an essential consideration in the sustainable use of this agroecosystem. Within the context of the savannas, Jiménez et al. (2001) proposed a hypothetical conservative agricultural production system to preserve benefits of soil fauna which integrated: (i) native vegetation plots possibly used as extensive pastures and as a reserve of biodiversity; (ii) permanent pastures for livestock systems that allow the establishment of important native earthworm biomass; (c) agro-pastoral systems with annual crops managed in rotation with temporary pastures and located contiguously to permanent pastures to maximize migration of populations. Integration of more intense production systems which build the ‘arable layer’ but thereafter revert to more conservative tillage practices may be viable alternatives whose sustainability should be examined at the landscape scale.

Acknowledgements

We thank CORPOICA-La Libertad and CORPOICA-Carimagua, Colombia, for their collaboration, and B. Volveras, C.G. Melendez, L. Chavez, J. Galvez, I. Corrales, J. Ricaurte, G. Borrero and A. Alvarez for their technical assistance. This study was partially supported by the Colombian Ministry of Agriculture and Rural Development.

References

Amézquita E. 1998. Propiedades físicas de los suelos de los Llanos Orientales y sus requerimientos de labranza. *In*: Romero G., Aristizábal D., Jaramillo C. (eds.). Memorias Encuentro Nacional de Labranza de Conservación, 28-30 April 1998, Villavicencio-Meta, Colombia.

Barrios E., Buresh R.J., and Sprent J.I. 1996. Organic matter in soil particle size and density fractions from maize and legume cropping systems. *Soil Biol.Biochem.* 28(2): 185-193.

Barrios E., Kwesiga F., Buresh R.J. and Sprent J.I. 1997. Light fraction soil organic matter and available nitrogen following trees and maize. *Soil Sci.Soc.Am.J.* 61(3): 826-831.

Decaëns, T., and Jiménez, J.J. 2002. Earthworm communities under an agricultural intensification gradient in Colombia. *Plant Soil* 240: (in press).

Friesen D., Thomas R., Rivera M., Asakawa N. and Bowen W. 1998. Nitrogen dynamics under monocultures and crop rotations on a Colombian savannas Oxisol. 16th World Congr. of Soil Sci., Montpellier, France, 20-26 August 1998.

Friesen D.K, Rao I.M., Thomas, R.J., Oberson A., and Sanz, I.J. 1997. Phosphorus acquisition and cycling in crop and pasture systems in low fertility tropical soils. *Plant Soil* 196:289-294.

Guimarães E.P., Sanz J.I., Rao I.M., Amézquita M.C. and Amézquita E. (eds). Sistemas Agropastoriles en sabanas tropicales de América Latina. CIAT, Cali, Colombia and EMBRAPA, Brasilia, Brazil. 313 p.

Jiménez J.J., Decaëns T., Thomas R.J., Mariani L., and Lavelle P. 2001. General conclusions, highlights, and further research needs. *In:* J.J. Jiménez and R.J. Thomas (eds). Nature's Plow: Soil Macroinvertebrate Communities in the Neotropical Savannas of Colombia. Chapter 24. CIAT, Cali, Colombia. pp.361-386.

Karlen D.L., Varvel G.E., Bullock D.G., and Cruse R.M. 1994. Crop rotations for the 21st Century. *Advances in Agronomy* 53:1-45.

Phiri S., Amézquita E., Rao I.M., and Singh B.R. 2001. Disc harrowing intensity and its impact on soil properties and plant growth of agropastoral systems in the llanos of Colombia. *Soil & Tillage Res.* 62:131-143.

Sanz J.I., Zeigler R.S., Sarkarung S., Molina D.L., and Rivera M. 1999. Sistemas mejorados arroz-pasturas para sabana nativa y pasturas degradas en suelos ácidos de América del Sur. *In:* Guimarães E.P., Sanz J.I., Rao I.M., Amézquita M.C. y Amézquita E. (eds). Sistemas Agropastoriles en sabanas tropicales de América Latina. CIAT, Cali, Colombia and EMBRAPA, Brasilia, Brazil. pp.232-244.

Thomas R.J., and Ayarza M.A (eds.). 1999. Sustainable land management for the Oxisols of the Latin American Savannas: Dynamics of soil organic matter and indicators of soil quality. CIAT, Cali, Colombia. pp. 231.

Agriculture, Ecosystems and Environment (in review)

Fallow management for soil fertility recovery in tropical Andean agroecosystems in Colombia

Edmundo Barrios , Juan G. Cobo, Idupulapati M. Rao, Richard J. Thomas, Edgar Amézquita, Juan J. Jiménez
Centro Internacional de Agricultura Tropical (CIAT), A.A. 6713, Cali, Colombia

Abstract

Andean hillsides dominate the landscape of a considerable proportion of Cauca Department in Colombia. The typical cropping cycle in the region includes monocrops or intercrops of maize (*Zea mays* L.), beans (*Phaseolus vulgaris* L.) and/or cassava (*Manihot esculenta* Crantz). Cassava is usually the last crop before local farmers leave plots to natural fallow until soil fertility is recovered and a new cropping phase can be initiated. Previous studies on land use in the Río Cabuyal watershed (6500 ha) show that a considerable proportion of land (about 25-30%) remains under natural fallow every year. The focus of our studies is on systems of accelerated regeneration of soil fertility, or improved fallow systems, as an alternative to the natural regeneration by the native flora. Fallow improvement studies were conducted on plots following cassava cultivation. The potential for soil fertility recovery after 12 and 28 months was evaluated with two fast growing trees, *Calliandra calothyrsus* Meissn (CAL) and *Indigofera constricta* L.(IND), and one shrub, *Tithonia diversifolia* (Hemsl.) Gray (TTH), as slash/mulch fallow systems compared to the natural fallow (NAT). All planted slash/mulch fallow systems produced greater biomass than the natural fallow. Greatest dry biomass (16.4 Mg ha^{-1} yr^{-1}) was produced by TTH. Other planted fallows (CAL and IND) produced about 40% less biomass than TTH and the control (NAT) about 75% less. Nutrient levels in the biomass were especially high for TTH, followed by IND, CAL, and NAT. The impact of fallow management on soil chemical, physical and biological parameters related to residual soil fertility during the cropping phase was evaluated. Soil parameters most affected by slash/mulch fallow systems included soil total N, available N (ammonium and nitrate), exchangeable cations (K, Ca, Mg and Al), amount of P in light fraction, soil bulk density and air permeability, and soil macrofauna diversity. Results from field studies suggest that the *Tithonia* slash/mulch fallow system could be the best option to regenerate soil fertility of degraded volcanic-ash soils of the Andean hillsides.

Key words: *Calliandra*, fallows, *Indigofera*, slash and mulch, soil quality, *Tithonia*

Introduction

In the humid tropics, a substantial proportion (36%) of agricultural land is on steep or very steep slopes (Wood et al., 2000). In mountainous regions of developing countries, these lands often play a central role in rural food security and increasingly supply urban and/or export food and forest product markets. Andean hillsides contribute to food production through agricultural systems but these systems are characterized by low productivity and limited use of nutrient inputs. They harbor a large proportion of the rural poor and are an important source of water for the urban population and agricultural and industrial activities downstream (CIAT, 1996a). Densely populated hillsides in the humid and sub-humid tropics are considered to be areas where diversification of cropping systems to include trees and shrubs could improve soil fertility, increase production of fuel-wood, and result in better watershed management (Young, 1997).

Traditional agricultural systems in Colombia’s tropical hillsides are based on shifting cultivation that involves slashing and burning of the native vegetation, followed by continuous cultivation and abandonment after 3-5 years because of low crop yields (Knapp et al., 1996). Leaving degraded soils to “rest” or “fallow” is a traditional management practice throughout the tropics for restoration of soil fertility lost during cropping (Sánchez, 1995). Successful restoration of soil fertility normally requires a long fallow period for sufficient regeneration of the native vegetation and establishment of tree species (Young, 1997). Increased pressure on land as a result of population growth has limited the possibility for long fallow periods. When purchasing power is low, one alternative to traditional fallows is to improve fallows with plants that replenish soil nutrient stocks faster than plants in natural succession (Barrios et al., 1997). Planted fallows are an appropriate technological entry point because of their low risk for the farmer, relatively low cost, and potential to generate additional products that bring immediate benefit while improving soil fertility (i.e. fuel-wood).

Slash and mulch agroforestry systems include alley cropping systems where pruned biomass from tree rows is applied in the alleys between the rows before planting (Kang et al., 1990). Alternatively, biomass transfer systems include the harvesting and transporting of biomass from one farm location (e.g., live fences) to another as a source of nutrients for the crop (Jama et al., 2000). Fallow enrichment of traditional slash/mulch systems of 'frijol tapado' in Costa Rica have also shown the importance of the inclusion of trees as a source of biomass and nutrients during soil fertility recovery (Kettler, 1997). In the Honduran 'quezungual' system trees are left in cropped fields and pruned periodically to keep competition low while providing plant residues for soil cover and as a source of nutrients (Hellin et al., 1999).

The volcanic-ash soils in Colombian hillsides generally contain high amounts of soil organic matter (SOM) but nutrient cycling through SOM in these soils is limited because most of it is chemically protected, which limit the rate of its decomposition (Phiri et al., 2001). The slash/mulch fallow system described in this work has the spatial design features of an agroforestry planted fallow system but involves prunings with the resulting biomass applied to the same fallow plot. This system is expected to accelerate nutrient recycling through increased biological activity in soils with high inherent nutrient reserves but low nutrient availability. In this paper we explore the agronomic features of this system as well as its impact on soil fertility recovery as measured by some soil chemical, physical and biological parameters before a cropping phase of maize.

Materials and Methods

Site description

The study was conducted on two farms in Pescador, located in the Andean hillsides of the Cauca Department, southwestern Colombia (2º48' N, 76º33' W) at 1505 m above sea level. The area has a mean temperature of 19.3°C and a mean annual rainfall of 1900 mm (bimodal). The experiment started in November 1997 and the fallow phase concluded after 27 months (FebruaryMarch 2000).

Soils in the area are derived from volcanic-ash deposition and are classified as Oxic Dystropepts in the USDA classification, with predominant medium to fine textures, high fragility, low cohesion, and shallow humic layers (IGAC, 1979). Soil bulk density is close to 0.8 Mg m^{-3}. Soils in the top 20 cm are moderately acid (pH $_{H20}$ = 5.1), rich in soil organic matter (C = 50 mg g^{-1}), low in base saturation (57%) and effective CEC (6.0 cmol kg^{-1}), and also low P availability (Bray-II P = 4.6 mg kg^{-1}). Low soil P availability is the result of high allophane content (52-70 g kg^{-1}) which increases soil P sorbing capacity (Gijsman and Sanz, 1998).

Experimental design

Experiments were set up at two locations in the Cauca Department hillsides on degraded soils previously cultivated with cassava for three years. Experiment BM1 was established at San Isidro Farm in Pescador. It was established as a random complete block (RCB) design with four treatments and three field replications. Treatments included two tree legumes, *Indigofera constricta* (IND) and *Calliandra calothyrsus* (CAL), one shrub, *Tithonia diversifolia* (TTH), and a natural regeneration or fallow (NAT). Plant species were selected on the basis of their adaptation to the hillside environment, ability to withstand periodical prunings, and the contrasting chemical composition of their tissues. The plot size was 18 m by 9 m. Experiment BM2 was established at the Benizio Velazco Farm also in Pescador. It was also established as a RCB design with three treatments due to limited space available and three field replications. Treatments included IND, CAL and NAT with same plot size and management as in BM1.

Glasshouse grown two-month old *Indigofera* and *Calliandra* plants, inoculated with rhizobium strains CIAT 5071 and CIAT 4910 respectively and a common *Acaulospora longula* mycorrhizal strain, were planted in the field at 1.5 x 1.5 m spacing for treatments IND and CAL respectively. *Tithonia* cuttings were initially rooted in plastic bags before transplanting to the field using a 0.5 x 0.5 m spacing. During the first two months all planted fallows were frequently weeded to facilitate rapid establishment, thereafter no additional weeding took place. The natural regeneration treatment, NAT, received no management at all and served as control since this is the common practice of local farmers once their soils have become unproductive. Treatments IND and CAL were pruned to 1.5 m height at 18 months after planting and weighed biomass was laid down on the soil surface. In the TTH treatment, plants were pruned to 20 cm six times, starting six months after planting, and weighed biomass laid on the soil surface. Pruning intensity in TTH was guided by farmers concern that this common weed may become too competitive if allowed to produce seeds. In the case of IND and CAL the strategy was to reduce the impact of prunings on stem diameter increase and thus value as fuel wood at the end of the fallow phase. Whole plot measurement of biomass production during each pruning event was carried out and a composited sub-sample taken for laboratory analyses before laying down the pruned biomass on the soil surface. All above-ground biomass was harvested after 27 months with the conclusion of the fallow phase and left on the soil surface until soil sampling.

Chemical analysis of plant materials

Subsamples of each plant material evaluated were analyzed for total carbon (C), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg). All plant material was ground and passed through a 1 mm mesh before analysis. C, N and P were determined with an autoanalyzer . Potassium, Ca and Mg were determined by wet digestion with nitric-perchloric acid followed by atomic absorption spectrometry (CIAT, 1993).

Soil sampling and analytical procedures

High soil variability has been identified as a major limitation to evaluation of soil management strategies because of the difficulty in finding significant treatment differences in the area of study. Several measures were taken to address this potential limitation including splitting field replications in half and treating them as subplots from the beginning of the experiment, grid sampling for a composite subplot sample, and using covariance analysis.

Twenty-five samples were collected in a grid pattern and composited for each subplot at 0-5, 5-10 and 10-20 cm respectively after 12 and 28 months under the four fallow treatments. Plant litter on the soil surface was carefully removed before collecting the soil samples. Samples from each plot were air-dried, visible plant roots removed, and the samples gently crushed to pass through a 2-mm sieve.

Whole soil was ground with a mortar and pestle to <0.3 mm and then analyzed for C, N, and P. Total organic C was determined by wet oxidation with acidified potassium dichromate and external heating followed by colorimetry (Anderson and Ingram, 1993). Total N and P whole soil were determined by digestion with concentrated sulfuric acid using selenium as a catalyst, followed by colorimetric determination with an autoanalyzer. Bray P and exchangeable K were extracted with Bray II solution followed by colorimetric and atomic absorption determination respectively. Exchangeable Ca and Mg, and Al were extracted with 1M KCl solution and determined as described before (CIAT, 1993). Nitrate and ammonium were extracted in 1M KCl solution and determined by colorimetry with an autoanalyzer. .

Separate soil samples were taken from each field replication after 28 months to assess soil physical, chemical and biological parameters at the end of the fallow period. Soil bulk density was determined every 5 cm soil depth by using 50 mm long cores with 50 mm internal diameter (Blake and Hartge, 1986). Measurements for other physical parameters used similar cylinders as those indicated above. Hydraulic conductivity was measured on undisturbed core samples using a constant head of water (Klute and Dirksen, 1986). Air permeability was determined by measuring the rate of air flowing in a core sample equilibrated at a suction of 7.5 KPa, using a Daiki DIK-5001 apparatus. Residual porosity was calculated as percentage of porosity remaining in the soil after subjecting it to a 20 KPa confined pressure at a suction equivalent to field capacity (Hakansson, 1990). Soil samples for chemical analyses were taken at three soil depths (i.e. 0-5, 5-10 and 10-20 cm).

Special attention was paid to the soil macrofauna communities (i.e. soil invertebrates larger than 2 mm) in BM1. The sampling was performed using the method recommended by the Tropical Soil Biology and Fertility Programme (TSBF) (Anderson and Ingram, 1993). In each fallow system and repetition two samples of 25 cm x 25 cm x 30 cm were taken at regular 5 m intervals. A metallic frame was used to isolate soil monoliths that were dug out with a spade and divided into 4 successive layers (i.e., litter, 0-10, 10-20, 20-30 cm). Each layer was then carefully hand-sorted in large trays and all macro-invertebrates seen with the naked eye were collected, counted, weighed and preserved in 75% alcohol, except for the earthworms which were previously fixed in 4% formalin for 2 or 3 days.

In the laboratory, invertebrates were then identified into broad taxonomic units (Orders or Families), counted and further grouped in 7 larger units, i.e., earthworms (Oligochaeta), termites (Isoptera), ants (Hymenoptera), beetles (Coleoptera), spiders (Arachnida), millipedes (Myriapoda), and “other invertebrates”. Density and biomass of each of these 7 major groups were determined in each slash/mulch fallow system. Biomass was expressed as fixed weight in alcohol, 19% lesser than live weight for earthworms and termites, 9% for ants, 11% for Coleoptera, 6% for Arachnida and Myriapoda and 13% for the “other invertebrates” (Decaëns et al., 1994).

Statistical analyses

Analyses of variance (ANOVA) for plant biomass and nutrient data from BM1 and BM2 experiments were conducted to determine the impact of experimental site and management regime on planted fallow species. Covariance analyses were conducted on soil data from the BM1 and BM2 experiments to determine the effect of fallow systems on soil parameters. In the case when covariance analysis for a parameter showed no significance, the Tukey’s Studentized Range Tests were used to compare treatment means; conversely, when covariance analysis for a parameter was significant, the General Linear Models Procedure of Least Square Means (LSM) was used to compare treatment means. ANOVA for soil physical parameters were used to compare treatment means at the end of the fallow period for BM1 and BM2 respectively. All statistical analyses were conducted using the SAS program (SAS Institute, 1990).

Results and Discussion

Initial soil conditions

Experimental sites were of the same soil type and had a similar recent cropping history as stated above; nevertheless, they showed differences in certain soil parameters probably as a result of previous differences in soil management. Soil at BM1 experimental site was generally more acid, had a lower total C, higher total P, and considerably higher Bray P and exchageable Al than soil at the BM2 experimental site (Table 1).

Biomass production

Total biomass production of the different slash/mulch fallow systems evaluated was higher in BM1 than in BM2, independent of treatment (Fig. 1). In BM1 the order of total biomass production was TTH>IND,CAL,NAT, while in BM2 the order was CAL,IND>NAT. Published values for leguminous trees in different agroforestry systems indicate average annual additions of dry matter biomass up to 20 Mg ha^{-1} yr^{-1} (Young 1997). The highest total biomass production, 17.1 Mg $ha^{-1}yr^{-1}$, corresponded to *T. diversifolia*, and was likely a result of fast growth and ability to withstand coppicing about every three months. This value is comparable to the mean dry biomass production of 18.0 Mg $ha^{-1}yr^{-1}$ for *Leucaena* *leucocephala* and greater than the 11.3 Mg $ha^{-1}yr^{-1}$ reported for *Senna siamea* in alley cropping systems (Van der Mersch et al., 1993). The mean biomass production of *C. calothyrsus* was 9.8 Mg $ha^{-1}yr^{-1}$ and 9.0 Mg $ha^{-1}yr^{-1}$ for *I. constricta*. The natural fallow (NAT), which represents the traditional fallow practice by local farmers, was dominated by herbaceous plants like *Panicum viscedellum* Scribn, *Emilia sonchifolia* (L.) DC., *Hyptis atrorubens* Poit, *Mellinis minutiflora* Beauv, *Richardia scabra* L., *Panicum laxum* SW and *Pteridium aracnoideum* (Kaulf.) Mabon. (Zamorano, 2000), and showed the lowest mean biomass accumulation (5.5 Mg $ha^{-1}yr^{-1}$). The difference observed in annual increments of dry matter production between IND and CAL as affected by experimental site suggests that *I. constricta* is more responsive to better soil conditions found in BM1 than *C. calothyrsus* while the latter is more tolerant to poorer soil conditions found in BM2. However, further multi-location testing of these species is needed to better define the environmental niches for these slash/mulch fallow species.

Table 1. Initial soil conditions for plow layer (0-20 cm) at experimental sites in BM1 and BM2

	pH	C tot	N (mg kg^{-1})			P (mg kg^{-1})		Ca	K	Mg	Al
	(H_20)	(mg kg^{-1})	total	NO_3	NH_4	total	Bray	(cmol kg^{-1})			
BM1	4.67	52674	4240	25.10	12.30	653.2	10.83	1.70	0.40	0.65	1.92
BM2	5.28	61741	4249	23.54	10.10	485.5	1.59	1.79	0.30	0.57	0.50

Amount of nutrients in the biomass

The relative contributions of nutrients through slash/mulch fallow management, expressed as percent of control (NAT), were generally highest in TTH (Table 2). Relative N contributions were highest in BM2 for both CAL and IND compared to BM1. This is possibly a result of the considerably lower (i.e. 40%) total aboveground biomass production in NAT in BM2 compared to BM1, because actual N inputs values were similar for both species in both experiments (data not shown). Research on the impact of nutrient contributions to the soil through the application of organic materials usually focus on N, increasingly on P, and least frequently on K, Ca or Mg. Nitrogen contributions through prunings of *L. leucocephala* and *S. siamea* in alley cropping systems were shown to contribute 307 kg ha^{-1} and 197 kg ha^{-1} respectively (Van der Mersch et al., 1993). Nitrogen contributions through slash/mulch systems TTH, IND and CAL in this study were 36%, 5% and 0.5% higher than for the *L. leucocephala* alley cropping systems mentioned above. Published values indicate that leguminous trees in alley cropping systems can contribute as much as 358 kg N, 28 kg P, 232 kg K, 144 kg Ca and 60 kg Mg per hectare (Palm, 1995). Nevertheless, nutrient availability in the soil is regulated to a large extent by the chemical composition or quality of plant tissues because they affect the rates of decomposition and nutrient release (Cadisch and Giller, 1997). All species used in this experiment have a N content greater than 2.5% which has been suggested as a conceptual threshold for N mineralization resulting in increased soil N availability to arable crops within a growing season (Palm et al., 2001). Nevertheless, while *T. diversifolia* and *I. constricta* decompose quickly because of their low lignin (6.9%, 4.6% respectively) and polyphenol (8.6%, 8.7%) contents and high *in vitro* dry matter digestibility (IVDMD) (72.4%, 77.4%), decomposition is slower in *C. calothyrsus* because of high lignin (14.5%) and polyphenol (18.4%) contents and low IVDMD (28.1%) (Cobo et al., 2002a). Recent studies also showed that fast decomposing, high quality plant materials (i.e. IND, TTH) generated high short-term N availability but low crop uptake; while slow decomposing, lower quality plant materials (i.e. CAL) resulted in greater N crop uptake presumably as a result of improved synchrony between soil nutrient availability and crop demand (Cobo et al., 2002b). Additional benefits from slash/mulch fallow systems include the contribution to soil nutrient pools from fine roots through root turnover and root dieback caused by pruning of above ground biomass. The importance of fine root and mycorrhiza turnover has generally been under emphasized as it has been shown in forest systems that they can contribute up to 4 times more N and up to ten times more P than above ground litterfall (Bowen, 1984). There is little information on the amount of nutrients supplied through roots in agroforestry systems (Palm, 1995). Root biomas of trees is usually between 20-50% of aboveground biomass, giving shoot:root ratios ranging from 4:1 to 1.5:1, but the proportion of roots becomes higher on nutrient- and/or water-limited soils (Young, 1997).

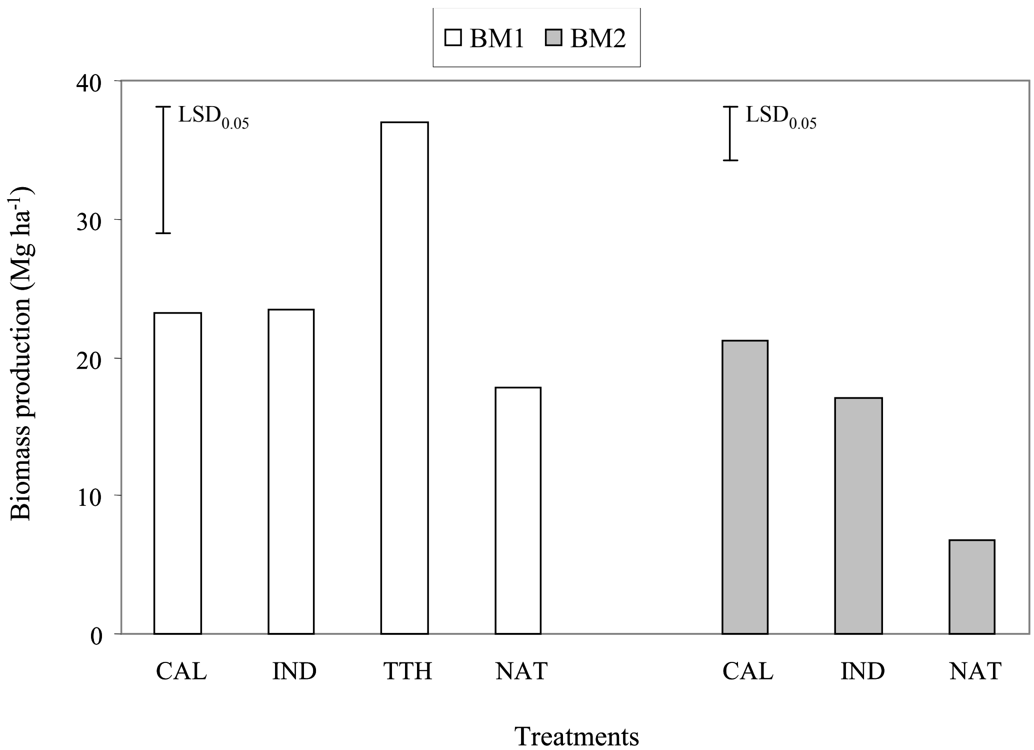


Fig. 1. Dry matter aboveground production by slash/mulch and natural fallow systems at the BM1 and BM2 sites after 27 months.

One important difference between slash/mulch fallow systems and biomass transfer systems is related to their long-term impact and sustainability. Slash/mulch fallow systems are likely to promote soil nutrient availability through remobilization of nutrients from less available soil nutrient pools. This may be a result of priming effects on soil mineralization processes triggered by labile C added with prunings as well as by root death and decomposition following slash/mulch. A considerable proportion of nutrients released is likely to be reabsorbed by the standing root biomass of fallow species and lead to new biomass growth. This cycle repeats with each slash/mulch event as nutrient recycling constitutes the basis of the functioning and sustainability of this cropping system. On the other hand, biomass transfer systems lead to variable levels of nutrient mining because they generate negative nutrient balances in soils under hedges and thus their long term use is limited as indicated by Gachengo et al. (1999) and Jama et al. (2000).

Table 2. Differences in total aboveground nutrient contributions by slash/mulch fallow systems compared to the natural fallow at BM1 and BM2 experiments

Experiment	Treatments	% of control (NAT)				
		N	P	K	Ca	Mg
BM1	CAL	176	5	-1	58	21
	IND	217	43	17	130	62
	TTH	215	225	283	351	223
BM2	CAL	606	120	138	269	311
	IND	608	164	199	507	540

Soil chemical parameters in slash/mulch planted fallow systems

Soil parameters showing significant differences among treatments included total N, available N (nitrate), exchangeable K, Mg, and Al for BM1 and available N (amonium, nitrate), and exchangeable K and Ca for BM2 (Table 3). Significant differences for most parameters, however, occurred after 12 or 28 months. The only parameters showing consistent significance across fallow age were total N in BM1 and exchangeable K in both BM1 and BM2. Because of high spatial variability, which is the characteristic feature of these hillside soils, significant changes are of considerable importance.

Table 3. Effects of four fallow systems on soil fertility parameters for plow layer (0-20 cm) at 12 and 28 months after establishment [ab].

		Means		Significance level			
		12	28	12 months		28 months	
Exp	Parameter	months	months	Cov*	Treat*	Cov	Treat
BM1	Ntot (mg kg^{-1})	4147	4645	0.317	0.050	0.099	0.043
	NO_3 (mg kg^{-1})	8.67	-	0.161	< 0.001	-	-
	K (cmol kg^{-1})	0.46	0.45	< 0.001	0.101	< 0.001	0.031
	Mg (cmol kg^{-1})	-	0.58	-	-	< 0.001	0.052
	Al (cmol kg^{-1})	1.61	-	0.011	0.028	-	-
BM2	NH_4 (mg kg^{-1})	14.1	-	0.547	0.040	-	-
	NO_3 (mg kg^{-1})	-	21.7	-	-	0.077	< 0.001
	K (cmol kg^{-1})	0.34	0.34	0.012	0.063	0.001	0.039
	Ca (cmol kg^{-1})	2.24	-	< 0.001	0.080	-	-

[a]For initial values refer to Table 1 [b]Data were subjected to covariance analysis.

***Cov = Covariable; Treat = Treatment**

Treatments means for soil parameters indicated are presented in Tables 4 and 5. Total soil N was highest (P < 0.05) in TTH, and CAL showed the second highest value after12 and 28 months of fallow duration (Table 4). After 12 months, NAT presented the lowest soil total N while IND had the lowest soil total N at the end of the fallow period (28 months). The beneficial effects of *T. diversifolia* on soil nutrients observed in the present study confirm previous published results of Gachengo et al. (1999), also on P-fixing soils. *T. diversifolia* is highly effective in scavenging soil nutrients as previously reported by

Jama et al. (2000). This may be a result of profuse rooting systems in association with native mycorrhizae as well as the capacity to stimulate mineralization of adsorbed P and utilize organic phosphorus. *C. calothyrsus* and *I. constricta*, on the other hand, are both N-fixers deriving respectively 37 and 42 % of their N from the atmosphere (CIAT, 1996b).

Table 4. Effect of fallow species on soil total N, amonium and nitrate for plow layer (0-20 cm) after 12 and 28 months of fallow period[abc]

		Fallow period				
		12 months			28 months	
Exp	Treat	Ntot ($mg\ kg^{-1}$)	NH_4 ($mg\ kg^{-1}$)	NO_3 ($mg\ kg^{-1}$)	Ntot ($mg\ kg^{-1}$)	NO_3 ($mg\ kg^{-1}$)
BM1	TTH	4390	-	6.61	4913	-
	CAL	4366	-	7.42	4717	-
	IND	4008	-	12.6	4266	-
	NAT	3824	-	8.07	4683	-
	SED	*169*	-	*1.69*	*159*	-
BM2	CAL	-	14.8	-	-	22.9
	IND	-	14.6	-	-	32.2
	NAT	-	13.0	-	-	8.10
	SED	-	*0.96*	-	-	*4.54*

[a]For initial values refer to Table 1

[b]Tukey's Studentized Range Tests was used to compare treatments means when covariable was not statistically significant ($P < 0.05$).

[c]For each parameter only treatment means are presented when their effect was shown significant in Table 3

After 12 months, slash/mulch fallow systems containing TTH showed the highest exchangeable K and lowest exchangeable Al ($P < 0.05$) in BM1 (Table 5). Studies in acid soils of Burundi have also found a reduction in exchangeable Al by green manure additions, suggesting complexing of Al by organic materials (Young, 1997). In BM2 highest exchangeable K and Ca values were found in IND and NAT respectively. At the end of the fallow phase (28 months), exchangeable K was highest for TTH overall, but the trend for the common treatments among BM1 and BM2 was the same, with NAT and IND contributing significantly ($P < 0.05$) more than CAL. Exchangeable Mg in BM1 showed the same trend as K with the difference that the IND fallow system led to the lowest soil values. The high concentration of cations, especially K in *T. diversifolia* biomass (Table 2), and the pruning management in TTH is likely to be responsible for the highest contribution to soil exchangeable cations by this slash/mulch fallow system.

The lack of significant changes in soil P parameters as a result of the slash/mulch fallow systems evaluated may, however, be influenced by the relative low amounts of P added to the soil compared with other nutrients like N and K (Palm et al., 1995) and also could be due to soils with a high P-sorption capacity (Rao et al., 1999).

Table 5. Effect of fallow species on soil exchangeable cations for plow layer (0-20 cm) after 12 and 28 months of fallow period[abc]

		Fallow Period									
		12 months						28 months			
Exp	Treat	Al ($cmol\ kg^{-1}$)		K ($cmol\ kg^{-1}$)		Ca ($cmol\ kg^{-1}$)		K ($cmol\ kg^{-1}$)		Mg ($cmol\ kg^{-}$	
BM1	TTH	1.24	b	0.54	a	-	-	0.60	a	0.67	a
	NAT	1.84	a	0.48	ab	-	-	0.49	ab	0.64	a
	IND	1.88	a	0.38	b	-	-	0.36	b	0.48	b
	CAL	1.49	ab	0.43	ab	-	-	0.34	b	0.53	ab
BM2	NAT	-	-	0.33	ab	2.32	a	0.38	a	-	-
	IND	-	-	0.39	a	2.19	b	0.36	a	-	-
	CAL	-	-	0.30	b	2.22	ab	0.29	b	-	-

[a]For initial values refer to Table 1

[b]Least Square Means (LSM) was used to compare treatment means when covariable was statistically significant ($P < 0.05$). Means in a column followed by the same letter do not differ significantly at $P = 0.05$.

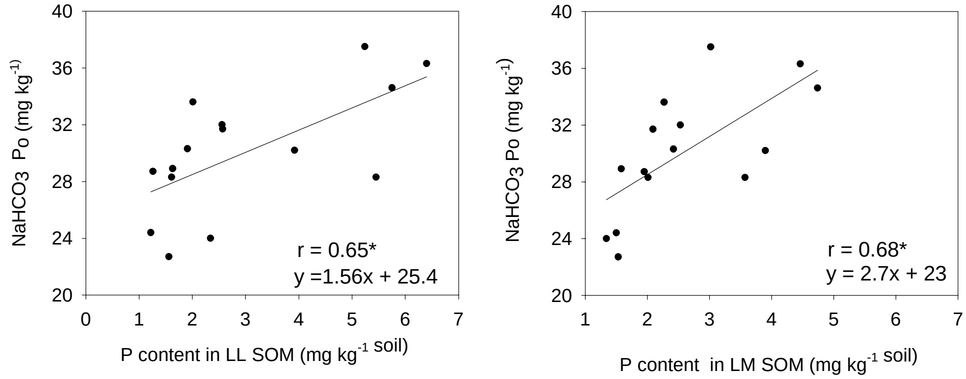
[c]For each parameter only treatment means are presented when their effect was shown significant in Table 3

Soil fractionation generally increases the capacity to detect soil changes in SOM as a result of treatment compared to bulk soil measures (Barrios et al., 1996; 1997). Recent results from Phiri et al. (2001) focusing on soil organic matter (SOM) (Meijboom et al., 1995) and P fractions (Tiessen and Moir, 1993), rather than conventional chemical analyses (e.g., Bray II P), indicate significant differences among treatments in experiment BM1 after 12 months. The slash/mulch fallow species in TTH, IND and CAL had an overall positive effect on soil fertility parameters when compared with the natural unmanaged fallow (NAT). *T. diversifolia* showed the greatest potential to improve SOM, nutrient availability, and P cycling because of its ability to accumulate high amounts of biomass and nutrients. The amount of P in the light (LL) and medium (LM) fractions of SOM correlated well with the amount of “readily available” P in the soil (Fig. 2). It is suggested that the amount of P in the LL and LM fractions of SOM could serve as sensitive indicators of “readily available” and “readily mineralizable” soil-P pools, respectively, in the volcanic-ash soils studied.

Soil physical parameters in slash/mulch planted fallow systems

Bulk density values reported for BM1 and BM2 are relatively low and are in agreement with published values for other volcanic ash soils (Shoji et al., 1993). After 28 months of fallow with the four systems, significant differences ($P < 0.05$) in bulk density were only found for the 0-5 cm soil depth of experiment BM2 (Table 6). While CAL and NAT were not different, IND showed significantly higher bulk density values (Table 7). A parameter showing significant treatment effects can result from low random error (i.e. bulk density) or a large separation of treatment means (i.e. air permeability) (Mead et al., 1993). The increased bulk density observed could be the result of a decrease in SOM levels. Although SOM levels in IND were lowest but not statistically significant (data not shown) in BM2, significantly lowest ($P < 0.05$) total N values were found in IND compared to other system treatment for BM1 (Table 4). Since soil total C and soil total N are highly correlated (Wild, 1988) we can assume that the *I. constricta* slash/mulch fallow generally promoted a reduction in SOM resulting in an increased soil bulk density.

A



B

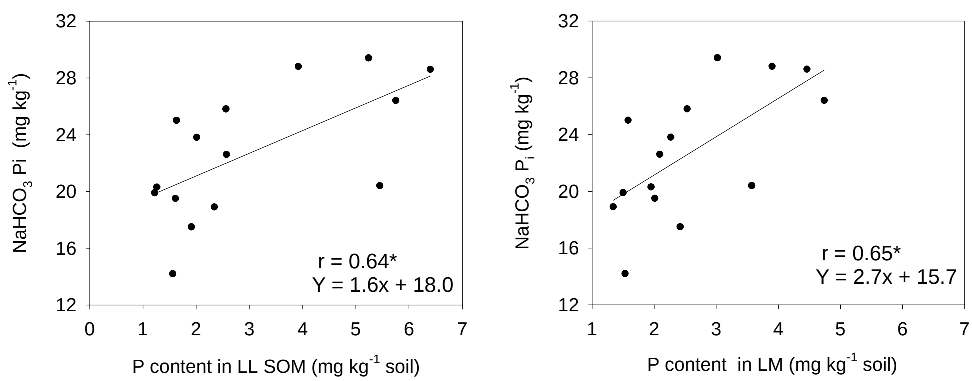


Fig. 2. The relationship between P content in the light (LL) and intermediate (LM) soil organic matter (SOM) fractions and sodium bicarbonate (NaHCO3) extractable organic P (A) and inorganic P (B) at BM1 after 12 months. The asterisk (*) indicates significance at a = 0.05.

Soil air permeability was sensitive to treatment differences in BM1 (Table 6). This parameter measures the resistance of soil to air-flow and is associated to bulk density and hydraulic conductivity. While TTH showed the highest values, CAL and NAT showed intermediate values and IND the lowest values (Table 7). These results indicate that TTH improved structural stability of surface soil presumably as a result of changes in pore size distribution which allowed better air flow while IND led to greater resistance to air flow than the control NAT.

Table 6. Probability table for effect of four fallow treatments on soil physical parameters in BM1 and BM2 after 28 months[a]

Soil Depth (cm)	Bulk density ($Mg\ m^{-3}$)		Hydraulic conductivity ($cm\ h^{-1}$)		Air permeability (75 cm suction) ($cm\ h^{-1}$)		Residual porosity (%)	
	BM1	BM2	BM1	BM2	BM1	BM2	BM1	BM2
0-5	0.289	0.036	0.844	0.695	0.018	0.775	0.413	0.552
5-10	0.474	0.581	0.379	0.152	0.273	0.747	0.104	0.554
10-15	0.124	0.449	0.693	0.354	0.412	0.763	0.595	0.503
15-20	0.118	0.149	0.424	0.488	0.199	0.566	0.167	0.578

[a]Data were subjected to analysis of variance

Soil macrofauna in slash/mulch planted fallow systems

The characterization of the soil macrofauna communities after 28 months of slash/much fallow treatments in BM1 showed taxonomically and functionally diverse taxa. A total of 22 taxonomic units (TU) were found. Macro-invertebrate total density ranged from 376.8 individuals (ind.) m^{-2} in TTH to 304.8 ind. m^{-2} in CAL. Conversely, macro-invertebrate biomass ranged from 18.2 g m^{-2} in IND to 6.1 g m^{-2} in TTH (Fig. 3). Other invertebrates corresponded to some nematodes (Mermithidae), hemipterans (Hemiptera) , snails (Gastropoda) and grasshoppers (Orthoptera). Termites (Isoptera) were almost absent from all fallow treatments, being less than 1% of total macro-fauna abundance.

Table 7. Effect of four fallow treatments on soil bulk density and air permeability at 0-5 cm soil depth in BM1 and BM2 after 28 months[a]

Treatment	Experiment BM2 Bulk density ($Mg\ m^{-3}$)	Experiment BM1 Air permeability ($cm\ h^{-1}$)
CAL	0.7	50.5
IND	0.8	33.8
NAT	0.69	64.7
TTH	-	91.6
SED	*0.03*	*12.6*

[a]For each parameter only treatment means are presented when their effect was shown significant in Table 6

The main groups of soil macro-invertebrates were rather abundant, especially ants (Hymenoptera). The abundance of ants, comprised of several species, was highest in TTH (254.8 ind.m^{-2}) and lower in IND and NAT (176 ind.m^{-2}). Earthworm density was lowest in TTH (19.2 ind.m^{-2}) and highest in IND (106.8 ind.m^{-2}). These two taxa were the main components of total macro-invertebrate biomass in all systems ranging from 46.9% in TTH to 73.1% in IND in the case of earthworm biomass. We found the exotic earthworm species *Pontoscolex corethrurus* (Glossoscolecidae) that is commonly found when tropical natural ecosystems are replaced by different production systems (Fragoso et al., 1999). In some Amazonian agroecosystems, the presence of this exotic has had a negative effect on soil properties, mainly due to loss of the original earthworm diversity rather than to the mere presence of this earthworm (Chauvel et al., 1999). Larvae of beetles (Coleoptera) were also highly abundant and their biomass was lowest in IND (78.8 g m^{-2}) and highest in TTH (120.8 gm^{-2}).

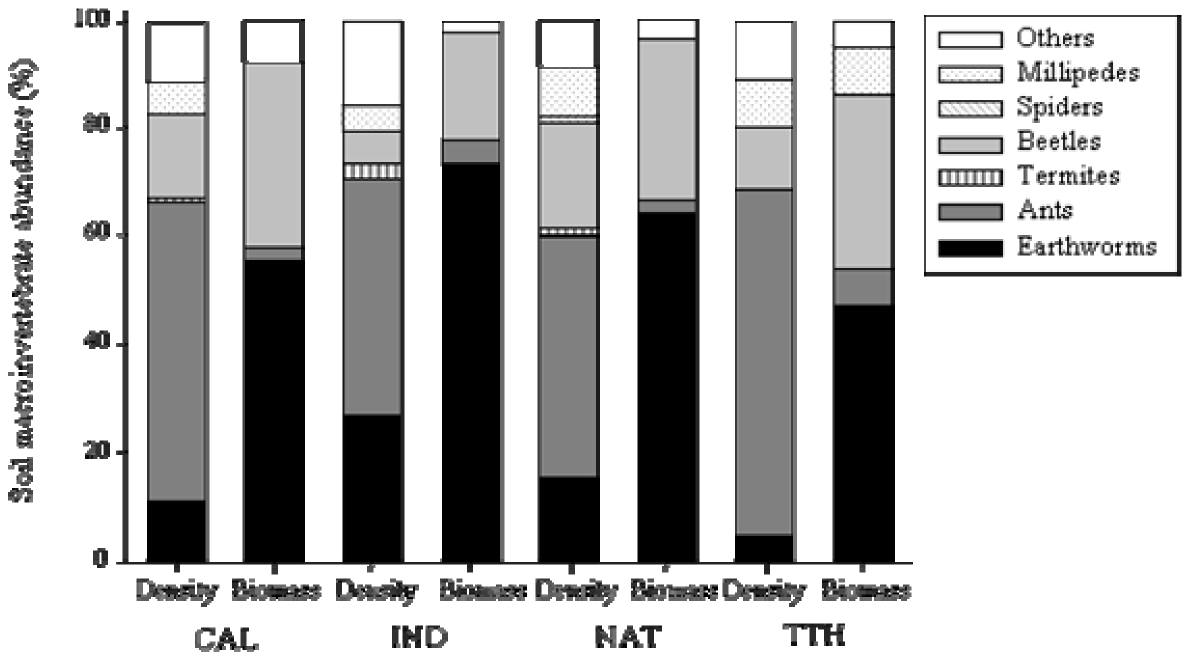


Fig. 3. Density and biomass of soil macroinvertebrate communities in the slash/mulch fallow systems at the BM1 site at the end of the fallow phase.

The impact of slash/mulch treatment differences is consistent with other results presented and suggest three generally distinct groups TTH, CAL+NAT, and IND. High ant activity in TTH, as indicated by high density, suggests that we may be underestimating the potential impact of *T. diversifolia* additions because a considerable proportion may be exported by ants to their nests. On the other hand, earthworm activity is well known for stimulating N mineralization rates (Barois et al., 1987; Lavelle et al., 1992; Decaëns et al., 1999; Rangel et al., 1999) and the observation of particularly high numbers of individuals in IND coincides with the observation of a reduction in total soil N and an increase in soil available N. The conspicuous presence of *P. corethrurus* in IND and the observation that compact casts increase soil compaction (Hallaire et al., 2000), because of the limited presence or absence of soil fauna able to decompact such casts (Blanchart et al., 1997, P.Lavelle pers.comm.), suggests that increased soil bulk density observed in IND may have been mediated by increased activity of this species.

Some groups of soil macroinvertebrates may have beneficial effects on some soil parameters evaluated but others, on the contrary, may cause damage since they constitute soilborne pests. Therefore, it is necessary to increase the level of resolution of identifications studies to the species level. This seems to be of particular relevance when using soil macrofauna as biological indicators of soil functioning and health (Pankhurst et al., 1997). Nevertheless, since information on soil fauna was not available at the beginning of the experiment and was limited to BM1, conclusions regarding the impact of production systems on the soil macrofauna communities must be considered preliminary.

Conclusions

Slash/mulch planted fallow systems evaluated in this study were more productive in terms of biomass production and nutrient recycling than the traditional practice of natural regeneration by native flora, suggesting that the objective of increased nutrient recycling was achieved. This study attempted to integrate understanding of the impacts of slash/mulch planted fallow systems on soil quality by simultaneously evaluating the chemical, physical and biological dimensions of the soil. The TTH slash/mulch fallow system proved to be the best option to recover the overall soil fertility of degraded soils following cassava monocropping in the study area. Nevertheless, its use may be limited in areas with seasonal drought as it is not very tolerant to extended dry periods. The CAL slash/mulch fallow system proved to be the most resilient as it produced similar amounts of biomass independent of initial soil quality and thus a candidate for wider testing as a potential source of nutrient additions to the soil and fuelwood for rural communities. The slower rates of decomposition in CAL, compared to IND and TTH, suggest that benefits provided may be longer lasting and potential losses would be reduced through improved synchronization between nutrient availability and crop demand. The IND slash/mulch fallow, on the other hand, showed more susceptibility to initial soil quality and this may limit its potential for extended use.

Increased soil bulk density as a result of decrease in SOM, observed in slash/mulch planted fallows using IND, was possibly mediated by the presence of large populations of the endogeic earthworm *P. corethrurus*. This earthworm species is known to stimulate N mineralization and to be responsible for soil compaction when a diverse macrofauna community capable of ameliorating soil physical structure is limited or absent. Although increased available N may have positive short-term impacts, the significant decrease in total soil N suggests that considerable N losses may be occurring during the fallow phase and benefits to subsequent cropping could be limited. Further multilocation testing is needed to confirm these observations, and also to study the 'fallow effect' on crop yield as well as the economic feasibility of slash-mulch fallow systems.

Acknowledgements

We are grateful to P. Lavelle for his comments on an earlier version of this manuscript. This work was possible due to the coordinated teamwork of staff from our soil biology, soil microbiology, soil chemistry, soil physics and plant nutrition labs. Special thanks to N. Asakawa and G. Ocampo for plant inoculations, E. Melo and H. Mina for greenhouse support, C. Trujillo, J. Cayapú and D. Franco for assistance in the field, E. Mesa and M.C. Duque for statistical support, and to the CIAT analytical services lab for routine lab analyses.

References

Anderson, J.M., Ingram, J.S.I., 1993. Tropical soil biology and fertility: A handbook of methods. 2nd edition. CABI, Wallingford, UK, 221 pp.

Barois, I., Verdier, B., Kaiser, P., Lavelle, P., Rangel, P., 1987. Influence of the tropical earthworm *Pontoscolex corethrurus* (Glossoscolecidae) on the fixation and mineralization of nitrogen. In: Bovincini Pagliai, A.M., Omodeo, P. (Eds.), On Earthworms. Selected Symposia and Monographs, Mucchi, Modena, Italy, pp. 151-158.

Barrios, E., Buresh, R.J., Sprent, J.I., 1996. Organic matter in soil particle size and density fractions from maize and legume cropping systems. Soil Biol. Biochem. 28, 185-193.

Barrios, E., Kwesiga, F., Buresh, R.J., Sprent, J.I., 1997. Light fraction soil organic matter and available nitrogen following trees and maize. Soil Sci. Soc. Am. J. 61, 826-831.

Blake, G.R., Hartge, K.H., 1986. Bulk density. In: Klute, A. (Ed.), Methods of Soil Analysis. Part 1 - Physical and Mineralogical Methods. 2nd edition. ASA, Soil Science Society of America, Inc., Madison, Wisconsin, USA, pp. 363-375.

Blanchart, E., Lavelle, P., Braudeau, E., Bissonnais, Y.I., Valentin, C., 1997. Regulation of soil structure by geophagous earthworms in humid savannas of Côte d'Ivoire. Soil Biol. Biochem. 29, 431-439.

Bowen, G.D., 1984. Tree roots and the use of soil nutrients. In: Bowen, G.D., Nambiar, E.K.S. (Eds.), Nutrition of Plantation Forests. Academic Press, London, UK, pp. 147-179.

Cadisch, G., Giller, K., 1997. Driven by nature. Plant Litter Quality and Decomposition. CABI, Wallingford, UK, 409 pp.

Chauvel, A., Grimaldi, M., Barros, E., Blanchart, E., Desjardins, T., Sarrazin, M., Lavelle, P., 1999. Pasture damage by an Amazonian earthworm. Nature 398, 32-33.

CIAT, 1993. Manual de Análisis de suelos y tejido vegetal: Una guía teórica y práctica de metodologías. Documento de trabajo No. 129. CIAT, Cali, Colombia.

CIAT, 1996a. Community management of watershed resources in hillside agroecosystems. Hillsides Program. Technical Report. CIAT, Cali, Colombia.

CIAT, 1996b. Productive and regenerative agricultural systems for marginal and degraded soils of tropical Latin America. Project No. 10. Soil and Plant Nutrition Unit. Annual Report. CIAT, Cali, Colombia.

Cobo, J.G., Barrios, E., Kass, D.C.L., Thomas, R.J., 2002a. Decomposition and nutrient release by green manures in a tropical volcanic-ash soil. Plant and Soil (in press).

Cobo, J.G., Barrios, E., Kass, D.C.L., Thomas, R.J., 2002b. Nitrogen mineralization and crop uptake from surface-applied leaves of green manure species on a tropical volcanic-ash soil. Biology and Fertility of Soils (in press).

Decaëns, T., Lavelle, P., Jiménez, J.J., Escobar, G., Rippstein, G., 1994. Impact of land management on soil macrofauna in the Oriental Llanos of Colombia. Eur. J. Soil Biol. 30, 157-168.

Decaëns, T., Rangel, A.F., Asakawa, N., Thomas, R.J., 1999. Carbon and nitrogen dynamics in ageing earthworm casts in grasslands of the eastern plains of Colombia. Biol. Fertil. Soils 30, 20-28.

Fragoso, C., Lavelle, P., Blanchart, E., Senapati, B.K., Jiménez, J.J., Martínez, M.A., Decaëns, T., Tondoh, J., 1999. Earthworm communities of tropical agroecosystems: origin, structure and influence of management practices. In: Lavelle, P., Brussaard, L., Hendrix, P. (Eds.), Management of Earthworm Communities in Tropical Agroecosystems. CAB International, Wallingford, UK, pp. 27-55.

Gachengo, C.N., Palm, C.A., Jama, B., Othieno, C., 1999. Tithonia and Senna green manures and inorganic fertilizers as phosphorus sources for maize in western Kenya. Agrofor. Syst. 44, 21-36.

Gijsman, A.J., Sanz, J.I., 1998. Soil organic matter pools in volcanic-ash soil under fallow or cultivation with applied chicken manure. Eur. J.Soil Sci. 49, 427-436.

Hakansson, I. 1990. A method for characterizing the state of compactness of the plough layer. Soil Tillage Res. 16, 105-120.

Hallaire,V., Curmi, P., Duboisset, A., Lavelle, P., Pashanasi, B., 2000. Soil structure changes induced by the tropical earthworm *Pontoscolex corethrurus* and organic inputs in a Peruvian Ultisol. Eur. J. Soil Biol. 36 (1), 35-44.

Hellin, J., Welchez, L.A., Cherrett, I., 1999. The Quezungual System: an indigenous agroforestry system from western Honduras. Agrof. Syst. 46, 229-237.

IGAC (Instituto Geográfico "Agustín Codazzi"), 1979. Estudio general de suelos de la parte alta de las cuencas de los Ríos Piendamó, Cajibío y Ovejas (Departmento del Cauca). Ministerio de Hacienda y Crédito Público, Santafé de Bogotá, Colombia, 302 pp.

Jama, B., Palm, C.A., Buresh, R.J., Niang, A., Gachengo, C., Nziguheba, G., Amadalo, B., 2000. *Tithonia diversifolia* as a green manure for soil fertility improvement in western Kenya: a review. Agrofor. Syst. 49, 201-221.

Kang, B.T., Reynolds, L., Atta-Krah, A.N., 1990. Alley farming. Adv.Agron. 34, 314-359.

Kettler, J.S., 1997. Fallow enrichment of a traditional slash/mulch system in southern Costa Rica: comparisons of biomass production and crop yield. Agrofor. Syst. 35, 165-176.

Klute, A., Dirksen, C., 1986. Hydraulic conductivity and diffusivity: laboratory methods. In: Klute, A. (Ed.). Methods of Soil Analysis. Part 1 - Physical and Mineralogical Methods. 2nd Edition. ASA, Soil Science Society of America, Inc., Madison, Wisconsin, USA, pp. 687-734.

Knapp, B., Ashby, J.A., Ravnborg, H.M., 1996. Natural resources management research in practice: the CIAT Hillsides Agroecosystem Program. In: Preuss, H-J.A. (Ed.), Agricultural Research and Sustainable Management of Natural Resources. LIT Verlag, Munster-Hamburg, Germany, pp. 161-172.

Lavelle, P., Melendez, G., Pashanasi, B., Schaefer, R., 1992. Nitrogen mineralization and reorganisation in casts of the geophagous tropical earthworm *Pontoscolex corethrurus* (Glossoscolecidae). Biol. Fertil. Soils 14, 49-53.

Mead, R., Curnow, R.N., Hasted, A.M., 1993. Statistical Methods in Agriculture and Experimental Biology, 2nd Edition. Chapman and may, London.

Meijboom, F.W., Hassink, J., van Noordwijk, M., 1995. Density fractionation of soil macroorganic matter using silica suspensions. Soil Biol. Biochem. 27, 1109-1111.

Palm, C.A., 1995. Contribution of agroforestry trees to nutrient requirements of intercropped plants. Agrofor. Syst. 30, 105-124.

Palm, C.A., Giller, K.E., Mafongoya, P.L., Swift, M.J., 2001. Management of organic matter in the tropics: translating theory into practice. Nutr. Cycl. Agroecosyst. 61, 63-75.

Pankhurst, C.E., Doube, B.M., Gupta, V.V.S.R. (Eds.), 1997. Biological Indicators of Soil Health. CAB International, Wallingford, UK, 451 pp.

Phiri, S., Barrios, E., Rao, I.M., Singh, B.R., 2001. Changes in soil organic matter and phosphorus fractions under planted fallows and a crop rotation system on a Colombian volcanic-ash soil. Plant and Soil 231, 211-223.

Rangel, A.F., Thomas, R.J., Jiménez, J.J., Decaëns, T., 1999. Nitrogen dynamics associated with earthworm casts of *Martiodrilus carimaguensis* Jiménez and Moreno in a Colombian savanna Oxisol. Pedobiologia 43, 557-560.

Rao, I.M., Friesen, D.K., Osaki, M., 1999. Plant adaptation to phosphorus-limited tropical soils. In: Pessarakli, M. (Ed.), Handbook of Plant and Crop Stress. Marcel Dekker, New York, USA, pp. 61-96.

Sánchez, P., 1995. Science in agroforestry. Agrofor. Syst. 30, 5-55.

SAS Institute, 1990. SAS/STAT Users Guide, Vol. 2. Version 6.1. SAS Institute, Cary, NC.

Shoji, S., Nanzyo, M., Dahlgren, R., 1993. Volcanic Ash Soils: Genesis, Properties and Utilization. Developments in Soil Science 21. Elsevier Science Publishers.

Tiessen, H., Moir, O., 1993. Characterization of available P by sequential extraction. In: Carter, M.R. (Ed.), Soil Sampling and Methods of Analysis. Lewis Publishers, Boca Raton, Florida, USA, pp. 75-86.

Van der Meersch, M.K., Merckx, R., Mulongoy, K., 1993. Evolution of plant biomass and nutrient content in relation to soil fertility changes in two alley cropping systems. In: Mulongoy, K., Merckx, R. (Eds.), Soil Organic Matter Dynamics and Sustainability of Tropical Agriculture. K.U. Leuven and IITA. John Wiley & Sons, Chichester, UK, pp. 143-154.

Wild, A. (Ed.), 1988. Russell's Soil Conditions and Plant Growth. 11th Edition. Longman Scientific and Technical, Burnt Mill, Harlow, Essex, England.

Wood, S., Sebastian, K., Scherr, S.J., 2000. Analyses of global ecosystems: agroecosystems. In: The Millenium Assessment of the State of the World's Ecosystems. IFPRI/WRI, Washington D.C. (in press).

Young, A., 1997. Agroforestry for Soil Management. 2nd edition. CAB International and ICRAF, New York, USA, 320 pp.

Zamorano, C. 2000. Dinámica de poblaciones de arvenses bajo el sistema de barbechos mejorados, Departamento Cauca, Colombia. BSc Thesis. Universidad Nacional de Colombia.

Soil Science Society of America Journal 66: 868-877 (2002)

Sequential phosphorus extraction of a ^{33}P-labeled oxisol under contrasting agricultural systems

S. Buehler[1], A. Oberson[1], I.M.Rao[2], E. Frossard[1] and D.K. Friesen[3]

[1]Institute of Plant Sciences, Swiss Federal Institute of Technology (ETH),
Eschikon 33, 8315 Lindau, Switzerland
[2]Centro Internacional de Agricultura Tropical, CIAT, A.a. 6713, Cali Colombia
[3]formerly IFDC/CIAT, now IFDC/CIMMYT Kenya, P.O. Box 25171, Nairobi, Kenya

Abstract

Chemical sequential extraction is widely used to divide soil phosphorus (P) into different inorganic and organic fractions, but the assignment of these fractions to pools of different availability, especially for low P tropical soils, is still matter of discussion. To improve this assignment, the effect of land-use systems and related P fertilizer inputs on size of P fractions and their isotopic exchangeability was investigated. A Colombian Oxisol, sampled from a long-term field experiment with contrasting management treatments was labeled with carrier free ^{33}P and extracted after incubation times of 4 hours, 1 and 2 weeks. Phosphorus concentrations (inorganic=P_i and organicP=P_o) and ^{33}P recovery in fractions sequentially extracted with resin (P_i), 0.5 *M* $NaHCO_3$ (Bic-P_i, Bic-P_o), 0.1 *M* NaOH (P_i, P_o), hot concentrated HCl (P_i, P_o) and residual P were measured at each time. Resin-P_i, Bic-P_i, NaOH-P_i and hot HCl-P_i were increased with fertilization, with highest increase for NaOH-P_i. The recovery of ^{33}P in the two soils with annual fertilizer inputs and large positive input-output P balances indicate that resin-P_i, Bic-P_i and NaOH-P_i contained most of the exchangeable P. In these soils the label moved with increasing incubation time from the resin to the Bic-P_i and NaOH-P_i fraction. As the ^{31}P content of these fractions remained constant, the transfer of ^{33}P suggests P exchange among these fractions. The organic or recalcitrant inorganic fractions contained almost no exchangeable P. In contrast, in soils with low or no P fertilization, more than 14% of added ^{33}P was recovered in NaOH-P_o and HCl-P_o fractions two weeks after labeling, showing that organic P dynamics are important when soil Pi reserves are limited.

Key words: Oxisol, land-use system, sequential P fractionation, short term P dynamics, ^{33}P labeling, metallic (oxy)hydroxides, soil microbial biomass

List of abbreviations: Bic-P: 0.5 *M* HCO_3-extractable P, CIAT: Centro Internacional de Agricultura Tropical, CORPOICA: Corporacion Colombiana de Investigacion Agropecuario, C_p: P concentration in the soil solution, P_i: inorganic P, P_o: organic P, SA: specific activity ($^{33}P/^{31}P$)

Introduction

Phosphorus (P) is an essential nutrient for plants and often the first limiting element in acid tropical soils. Profound understanding of the P dynamics in the soil/plant system and especially of the short- and long-term fate of P fertilizer in relation to different management practices is essential for the sustainable management of tropical agroecosystems (Friesen et al., 1997). Chemical sequential extraction procedures have been and still are widely used to divide extractable soil P into different inorganic and organic fractions (Chang and Jackson, 1957; Bowman and Cole, 1978; Hedley et al., 1982; Cross and Schlesinger, 1995). The underlying assumption in these approaches is that readily available soil P is removed first with mild extractants, while less available or plant-unavailable P can only be extracted with stronger acids and alkali. In the fractionation procedure developed by Hedley et al. (1982) and modified by Tiessen and Moir (1993), the P fractions (in order of extraction) are interpreted as follows. Resin-P_i represents inorganic P (P_i) either from the soil solution or weakly adsorbed on (oxy)hydroxides or carbonates (Mattingly, 1975). Sodium bicarbonate 0.5 *M* at pH 8.5 also extracts weakly adsorbed P_i (Hedley et al., 1982) and easily hydrolysable organic P (P_o)-compounds like ribonucleic acids and glycerophosphate (Bowman and Cole, 1978). Sodium hydroxide 0.5 *M* extracts P_i associated with amorphous and crystalline Al and Fe (oxy)hydroxides and clay minerals and P_o associated with organic compounds (fulvic and humic acids). Hydrochloric acid 1 *M* extracts P_i associated with apatite or octacalcium P (Frossard et al., 1995). Hot concentrated HCl extracts P_i and P_o from more stable pools. Organic P extracted at this step may also come from particulate organic matter (Tiessen and Moir, 1993). Residual P, i.e. P that remains after extracting the soil with the already cited extractants, most likely contains very recalcitrant P_i and P_o forms.

Several studies related these different P fractions in tropical soils to plant growth (Crews, 1996; Guo and Yost, 1998) or showed the influence of land-use and the fate of applied fertilizers (Iyamuremye et al., 1996; Linquist et al., 1997; Lilienfein et al, 1999; Oberson et al., 1999), and partly resulted in contrasting assignments of fractions to pools of different availability. By comparing the amounts of P extracted from the surface horizons of Brazilian Oxisols that had been under different land-use systems for 9-20 years, either unfertilized or with mineral P fertilizer application, Lilienfein et al. (1999) showed that most of the fertilizer was recovered in the Bic- and NaOH-P_i fractions, irrespective of the land-use system (resin-P_i was not measured). In a 4-year field study conducted on a Hawaiian Ultisol, Linquist et al. (1997) recovered one year after fertilizer application almost 40% of the applied triple super phosphate (TSP) fertilizer in the hot HCl and H_2SO_4 fractions. Oberson et al. (1999) showed that in an Oxisol managed as a legume-grass pasture for 15 years resin-P_i, Bic- and NaOH-P_i as well as NaOH-P_o levels were maintained at a higher level over the whole year in comparison to the same soil with the same total P content but managed as a grass only pasture. Iyamuremye et al. (1996) found an increase of resin-P_i, Bic-P_i and -P_o as well as NaOH-P_i after addition of manure or alfalfa residues to acid low-P soils from Rwanda. In the study of Guo and Yost (1998), resin-P_i, Bic- and NaOH-P_i were most depleted by plant uptake on highly weathered soils. NaOH-P_i was important in buffering available P supply while significant depletion of organic fractions could rarely be measured.

A possible method to gain information about the availability of different P fractions is to label soil P, fertilizers or plant residues before applying the sequential fractionation scheme (MacKenzie, 1962; Weir and Soper, 1962, Dunbar and Baker, 1965). Two studies followed the movement of labeled P from plant residues to soil P fractions applying a modified Hedley (Daroub et al., 2000) or the Chang and Jackson (1957) fractionation procedures (Friesen and Blair, 1988). They found that at six or eleven days, respectively, after plant residue addition between 20 and 50 % of the label was extractable as P_i with a resin (Daroub et al., 2000) or with NH_4Cl and NH_4F (Friesen and Blair, 1988). For longer incubation periods up to 34 days, Daroub et al. (2000) showed a subsequent movement of the label from the resin-P_i fraction to the NaOH-P_i fraction. The results obtained in these studies suggest that, in tropical soils, the amounts of P in the different pools measured by sequential P extraction procedures and the fluxes of P between pools are controlled both by physico chemical factors (sorption/desorption) and by biological reactions (immobilization/mineralization). However, the importance of these different reactions for different land-use systems, such as monocropping, pasture or intercropping, remain largely unknown.

The objective of this study was to assess the effect of different land-use systems (native savanna, rice monocropping, rice green manure rotation, grass legume pasture) on some physico chemical and biological reactions involved in P cycling in a Colombian Oxisol. Surface soil sampled in the different cropping systems was labeled with carrier-free radioactive P (^{33}P). After various incubation times, P was sequentially extracted by the modified Hedley procedure (Tiessen and Moir, 1993) and ^{31}P and ^{33}P were measured in each fraction.

Materials and Methods

Soils included in the study were sampled during the rainy season in September 1997 from a field experiment (Friesen et al., 1997) located at CORPOICA-CIAT (Corporacion Colombiana de Investigacion Agropecuario; Centro Internacional de Agricultura Tropical) research station, Carimagua, Meta, Colombia

(4°30'N, 71°19'W). Mean annual temperature is 27° C, average rainfall 2200 mm. The soils are well drained Oxisols (Kaolinitic isohyperthermic Typic Haplustox) of clay loam texture (Table 1).

The surface soil layer (0-20 cm) was sampled in the long-term "Culticore" field experiment, which was established in 1993 with the objective to test the effect of different farming systems on plant productivity and soil fertility (Friesen et al., 1997). The experiment had a split-plot design with four replicates with treatment sub-plots of 0.36 ha size. The soil samples used for this study were taken at random in two replicates of each treatment and the replicates were mixed for the laboratory analysis. For our study, the following treatments were included.

1. SAV (Native savanna): native grassland annually burned in February, not grazed; no fertilizer application.
2. GL (Grass-legume pasture): rice in 1993, with undersown pasture, since then grass-legume pasture with *Brachiaria humidicola* CIAT 679, *Centrosema acutifolium* CIAT 5277, *Stylosanthes capitata* CIAT 10280, and *Arachis pintoi* CIAT 17434. The pasture was partly resown for renovation in June 1996 with legumes (the same *Arachis pintoi*, additionally *Centrosema acutifolium* cv Vichada CIAT 5277 and *Stylosanthes guianensis* CIAT 11833). Grazing intensity was on average 2.7 steers ha^{-1} during 15 d followed by a 15 d ley regrowth phase.
3. CR (Continuous rice): rice (*Oryza sativa* cv Oryzica Sabana 6, cv Oryzica Sabana 10 since 1996) grown in monoculture; one crop per year followed by a weedy fallow incorporated with early land preparation at the beginning of the rainy season before sowing rice.
4. RGM (Rice green manure rotation): Rice followed by cowpea (*Vigna unguiculata,* var. ICA Menegua) in the same year. The legume was incorporated at the maximum standing biomass level in the late rainy season before sowing rice in the following rainy season.

Before establishing the treatments, GL, CR, and RGM on savanna, the soil was conventionally tilled after burning the native vegetation. At the beginning of the experiment all treatments except SAV were limed using 500 kg dolomitic lime ha^{-1}. Fertilization of rice was 80 kg N ha $year^{-1}$ (urea, divided among three applications), 60 kg P ha $year^{-1}$ (triple superphosphate), 99 kg K as KCl, 15 kg Mg and 20 kg S (as $MgSO_4$) and 10 kg Zn ha^{-1} at establishment and according to plant needs afterwards. With cowpea additionally 20 kg N and 40 kg P ha $year^{-1}$ and 60 kg K, 10 kg Mg, 13 kg S and 10 kg Zn ha^{-1} at establishment and in adequate rates afterwards were applied. The introduced pasture (GL) received additional fertilization only in 1996 (per ha: 20 kg P, 20 kg Ca (lime), 10 kg Mg (lime), 10 kg S (elemental) and 50 kg K (KCl)). Phosphorus input-output balances were estimated by subtracting the P removed from the system by grain and/or with animal live weight gains from the P applied in mineral fertilizers. Phosphorus exports in grain were calculated by multiplying weighed rice grain yields with measured P contents in grains. P exported in the animals was assumed to be 8 g per kg of live weight gain. Live weight gains in GL were on average 68 kg ha^{-1} yr^{-1} (Oberson et al., 2001). Cultivated soils were tilled to a maximum of 15 cm depth.

Topsoil samples (0-20 cm) were air-dried and sieved at 2 mm before they were used for chemical analysis in the analytical service laboratory of CIAT or shipped to Switzerland where they were stored in air-dried condition until use for the fractionation experiment in 2000.

Soil Characterization

Bray-II P was extracted using dilute acid fluoride (0.03 *M* NH_4F, 0.1 *M* HCl) at 1:7 soil solution ratio using 2 g soil and 40 sec shaking time. Total soil P (P_{tot}) was determined on samples of 0.25 mg soil with addition of 5 mL concentrated H_2SO_4 and heating samples to 360° on a digestion block with subsequent stepwise (0.5 mL) additions of H_2O_2 until the solution was clear (Thomas et al., 1967).

Table 1. Selected chemical and physical properties of the surface soil (0-20 cm) of studied Colombian Oxisol under different gricultural systems. Values are the average of four analytical replicates, except Fe- and Al-contents (three replicates#).

Treatment †	Total C	Total N	pH in water	Al-Saturation	Fe_{d} ‡	Fe_{ox} §	Al_{d} ‡	Al_{ox} §	Clay	Bulk density
	g kg^{-1}			%	g kg^{-1}				%	Mg m^{-3} ¶
SAV	27	1.64	4.8b	86.8b	26.7	3.6	7.8	2.0	35.0a	1.27
GL	29	1.55	4.9b	71.7a	26.4	3.6	7.7	2.0	39.3b	1.27
CR	26	1.45	4.3a	75.4a	26.2	3.7	7.6	2.0	39.9b	1.21
RGM	26	1.49	4.3a	76.3a	26.9	3.5	7.8	2.0	39.0b	1.24

† see Table 1.
‡ Extraction with dithionite.
§ Extraction with oxalate.
# Means followed by the same letter are not significantly different (*P*=0.05) by Tukey's multiple range test. The absence of ` letter in a column shows that no significant differences were observed between the treatments

Microbial P, C and N (P_{Chl}, C_{Chl} and N_{Chl}) were determined on the same moist, preincubated samples as for the sequential P fractionation by extraction, of chloroforme fumigated and unfumigated samples, with Bray I (0.03 *M* NH_4F, 0.025 *M* HCl) (P_{Chl}) (Oberson et al., 1997) or K_2SO_4 (C_{Chl} and N_{Chl}) (Vanceet al., 1987). No k-factors (Brookes et al., 1982; Hedley and Stewart, 1982; McLaughlin et al., 1986) were used to calculate P_{mic}, C_{mic} or N_{mic} from measured P_{Chl}, C_{Chl} and N_{Chl} as there exist no proper estimates for these acid tropical soils (Gijsman et al., 1997). P_{Chl} was corrected for sorption of released P according to Oberson et al. (1997). Dithionite-citrate-bicarbonate extractable and oxalate extractable Fe and Al (Fe_d, Fe_{ox}, Al_d, Al_{ox}) were determined according to Mehra and Jackson (1960) and McKeague and Day (1966). The mineralogy of the soils was determined on total soil samples, pretreated with H_2O_2 to remove organic C, using X-ray diffraction analysis (XRD) (Table 1). The samples were ground under acetone in a tungsten carbide vessel of a vibratory disk mill (Retsch RS1) for 10 minutes. Longer grinding times were not applied due to the detrimental effect that further grinding can have on the crystallinity of minerals, especially Fe (hydr)oxides (Weidler et al., 1998). For the Cu Kα, the Bragg-Brentano geometry was chosen as an XRD routine setup. The measurement were carried out on a Scintag XDS 2000 equipped with a solid state detector from 2 to 52 °2 \θ with steps of 0.05 °2\θ and counting times of 16 seconds.

Sequential P Fractionation of Labeled Soils

Before starting the sequential P fractionation, the soils were preincubated in a climate chamber (24°C and 65 % relative atmospheric humidity, no light) for two weeks in portions of 100 g at 50% of their water holding capacity (300 g water kg^{-1} soil dry weight). Soil water content was controlled and adjusted every other day by weighing.

Subsamples of preincubated soils were labeled in portions of 15 g with 120 MBq $^{33}P\ kg^{-1}$ which were added with 10 µl deionized water per g soil. The mass of P introduced with the ^{33}P label can be neglected (<2.5 x 10^{-3} g P g^{-1} soil, Amersham product specification, July 2000). Therefore, the term 'P concentration' always refers to ^{31}P and specific activities (SA) are calculated as:

$$SA\ (Bq\ g^{-1}\ P) = {}^{33}P/{}^{31}P \qquad \text{[Eq. 1]}$$

Soil P was fractionated sequentially with three replicates per soil following the modified method of Hedley et al. (1982), as described in Tiessen and Moir (1993), with HCO_3-saturated resin strips (BDH # 55164, 9 x 62 mm), followed by 0.5 *M* $NaHCO_3$ (referred to as Bic-P), 0.1 *M* NaOH, (these first three steps each with an extracting time of 16 h) and concentrated hot HCl at 80° C for 10 minutes. The step using diluted cold HCl was omitted, as Ca-phosphates are only present at very low levels or are absent in highly weathered acidic soils (Agbenin and Tiessen, 1995), as shown for the soils used in this study by Friesen et al. (1997). Residual P was extracted as described previously for determination of P_{tot}.

The amount of soil extracted was doubled from 0.5 to 1 g using the original volumes of extractants (2 resin strips in 30 mL H_2O, 30 mL $NaHCO_3$, 30 mL NaOH, 15 mL concentrated HCl, 5 mL conc. H_2SO_4) in order to get higher ^{33}P-concentrations in the extracts. This was preferred to the alternative of higher label application as the radiation might affect microbes (Halpern and Stöcklin, 1977). After each extraction, the samples were centrifuged at 25000 x g for 10 minutes before filtering the solutions of the Bic- and the NaOH-extraction through 0.45 m pore size millipore filters (Sartorius, cellulose acetate), and the hot HCl and residual P extract through a Whatman filter Nr. 40.

Phosphorus concentration in all extracts was measured after neutralization by the Murphy and Riley (1962) method. This method was used directly, after neutralization of the extracts, for the P recovered from the resin strip and for P_i determination in the HCl extract. Organic matter was first precipitated by acidification in the Bic- and the NaOH-extracts prior to P_i determination (Tiessen and Moir, 1993). Total P (P_t) in the Bic-, the NaOH- and the HCl-extracts was measured after digestion of P_o with potassium persulfate (Bowman, 1989). Organic P was calculated as the difference between total P and P_i in the Bic-, NaOH- and hot HCl extracts.

To partition soluble $^{33}P_i$ and $^{33}P_o$ in the Bic-, the NaOH- and the hot HCl-extracts into separate solutions before counting, 5 mL of the extracts were shaken with acidified ammonium molybdate dissolved in isobutanol (Jayachandran et al., 1992). With this method, P_i is extracted into the isobutanol while P_o remains in the aqueous phase. The complete recovery of P_i in the isobutanol phase was verified with the addition of a standard amount of ^{33}P in 0.5 *M* HCO_3, 0.1 *M* NaOH and in 2.3 *M* HCl; recovery rates of added ^{33}P in the isobutanol phase were between 97 % and 103 %, which was not significantly different from 100%. Counts in the aqueous phase were 1.1 % (HCO_3), 0.3 % (NaOH) and 0.1 % (HCl) of the original solutions showing that hardly any P_i goes into this phase. Determination of total P in the aqueous phase is not possible because the presence of the molybdate interferes with the analysis (Jayachandran et al., 1992).

The radioactivity in each phase was determined with a liquid scintillation analyzer (Packard 2500 TR) using Packard Ultima Gold scintillation liquid in the ratio (extract to liquid) 1:5. The values were corrected for radioactive decay back to the day of soil labeling. All extracts were tested for possible quenching effects by adding defined ^{33}P spikes. Quenching in the acid resin eluate could be prevented by dilution of 250 μl eluate with 750 μl deionized water for counting. The quench effect in the hot concentrated HCl extract could be avoided by counting in the solutions separated with acidified isobutanol because the separated phases were not affected by quenching. All other extracts were not affected by quench effects.

The recovery of the label as sum of all fractions, including residual P, was never complete. Therefore, subsamples of the soil residue after final acid digestion were dried and weighed into scintillation vials. These subsamples were then counted after addition of 1 mL water and 5 mL of scintillation cocktail.

Isotopic Exchange Kinetics

The procedure of isotopic exchange kinetics was used to assess the exchangeability of P_i in the soils sampled in the different land-use systems. The method was conducted as described by Fardeau (1996). Suspensions of 10 g of soil and 99 mL deionized water were shaken for 16 h on an overhead shaker to reach a steady state equilibrium for P_i. Then, at t = 0, 1 mL of carrier free $H_3{}^{33}PO_4$ tracer solution containing 1.2 MBq was added to each continuously stirred soil water suspension. Three subsamples were taken from each sample after 1, 10 and 100 minutes, immediately filtered through a 0.2 μm pore size micropore filter, and the radioactivity in solution was measured by liquid scintillation as described previously. To determine the ^{31}P concentration in the soil solution (C_p, mg P L^{-1}) 10 mL of the solution were filtered through a 0.025 μm filter (Schleicher & Schuell, NC 03) at the end of the experiment. The smaller filter pore size was used to exclude any influence of suspended soil colloids on C_p determination (Sinaj et al., 1998). The P concentration in the filtrate was measured in a 1 cm cell using the Malachite green method (Ohno and Zibilske, 1991) with a Shimadzu UV-1601 spectrophotometer. As the concentrations in the solutions of SAV and GL were close to the detection limit, they were additionally measured in samples concentrated by evaporation (5:1). This procedure resulted in C_p values that were not significantly different from the non-concentrated solutions.

Assuming that at any given exchange time the specific activity (SA) of inorganic phosphate in the solution is equal to the SA of the total quantity of phosphate which has been isotopically exchanged, it is possible to calculate the amount of isotopically exchanged P (E_t, mg P kg^{-1} soil). The amount of P exchangeable within one minute (E_1), indicating the immediately available P, is expressed as (Fardeau, 1996):

$$E_1 = R \times 10 \times C_p / r_1 \qquad \text{[Eq. 2]}$$

where R is the introduced radioactivity and r_1 is the radioactivity remaining in solution after 1 minute of isotopic exchange. The factor 10 results from the soil solution ratio of 1:10.

Statistical Analysis

The effects of land-use systems and incubation time after labeling on P fraction size were tested by two-way ANOVA and Tukey's multiple range over all treatments and times of fractionation. A separate one-way ANOVA was used to test the difference on label recovery and fraction size between samples labeled in soil water ratio 1:10 and samples labeled in incubated moist state 4 hours after labeling. Percentage recovery data were log-transformed to meet the requirements of analysis of variance. Time and soil treatment influences on the Sas of each fraction were tested by a two-way ANOVA and, as the interaction time X treatment was significant for all fractions, the treatment influence was tested for each repitition in time of sequential fractionation, separately.

Results and Discussion

The mineralogy and the Fe and Al (oxy)hydroxides contents of the surface soil from the four treatments was normal for this type of soil (Gaviria, 1993). On average of all treatments, the soil contained 68% quartz, 23% kaolinite, 4% anatase, 3% gibbsite, 2% rutile, and <1% vermiculite. There were no significant differences among the different land-use systems (SAV, GL, CR, RGM). This implies that any difference seen in the P dynamics among land-use systems was mainly due to the land-use system and not to differences in the soil mineralogy.

Total Soil P and P Balance Induced by the Different Treatments

The amounts of total P directly extracted from the soil samples (P_{tot}) were not significantly different from the sum of P (P_{sum}) extracted in the different fractions of the sequential extraction for SAV and CR while the direct extraction led to significantly higher values (P<0.05) for GL and RGM (Table 2). To evaluate whether differences in total P content in soils were related to P fertilization, the increase in P_{tot} content (calculated as the difference between total P extracted from fertilized GL, CR or RGM) and P_{tot} extracted from non fertilized SAV was compared to the estimated P balance of these treatments (significant correlation, r^2=0.87; P<0.001). The increases in P_{tot} were of the same order of magnitude as the calculated P balance. Given the imprecision of the methods used to determine total P contents (O'Halloran, 1993) and of the estimations made to calculate the P balance, these results suggest that most of the P added with fertilizers and not taken up by plants remained in the surface layers of the studied soils. Except for the CR soil these results agree well with Oberson et al. (2001). In their study only about half of the calculated positive P balance was recovered in total P. The sampling depth of 0-10 cm might explain this difference: soil tillage may have mixed P in the 0-10 cm soil layer with soil in the 10-20 cm layer, resulting in incomplete recovery of P in the 0-10 cm sampling depth.

Table 2. P status and calculated P balances of the studied Oxisol under different land-use systems. Total P as sum of the sequential P fractionation (P_{sum}) or extracted directly with H_2O_2 and H_2SO_4 (P_{tot}).

Treatment†	Bray II P‡	P_{sum} ‡	ΔP_{sum}§	P_{tot} ‡	ΔP_{tot}§	P-Balance¶
	mg kg^{-1}					
SAV	0.9a	165aA	0	172aA	0	0
GL	2.0b	190bA	25	213bB	41	28
CR	17.2c	290cA	125	293cA	121	92
RGM	35.5d	335dA	170	376dB	205	153
F-test (soil)	***	***		***		

† see Table 1.
‡ P concentrations followed by the same lower case letter (within columns) or upper case letter (comparison of P_{sum} and P_{tot} within rows) are not significantly different (P=0.05) according to Tukey's test.
§ Δ P calculated as the difference between P_{sum} or P_{tot} of fertilized treatments – SAV.
¶ Calculated by subtracting the P removed by grain and/or animals from the P applied with mineral fertilizer.

Isotopic Exchange Characteristics

The effect of the four land-use systems on P_i exchangeability in the surface layer of the studied soil is presented in Table 3. The ratio r_1/R, which is inversely correlated to the P sorbing capacity of soils (Frossard et al., 1993), was below 0.05 for all treatments suggesting that these soils have a high P sorbing capacity (Frossard et al., 1993). Furthermore, the r_1/R-values of the four treatments were positively correlated with the directly extracted total soil P (r^2=0.76 P<0.001). This suggests that the different land-use systems have resulted, through their different P fertilization and cropping, in different sorption rates of P_i on soil minerals. Since in Oxisols P sorption is governed by the Al and Fe (oxy)hydroxides, these treatments probably induced different degree of P_i saturation on the soil metallic (oxy)hydroxides such as gibbsite, which was identified in the soil from these treatments.

The P_i concentration in the soil solution (C_p) was close to the detection limit in SAV, GL and CR treatments (Table 3). Although significantly different between all treatments, C_p was significantly increased only in the RGM treatment (P<0.001). In SAV, GL and CR, C_p was much lower than the critical concentration needed to sustain optimal growth for a large range of crops (Kamprath and Watson, 1980; Fox, 1981). The P_i concentration in the soil solution was not correlated with the total soil P content. The clear C_p increase in RGM was therefore not only due to an increase in total P but also to other mechanisms. The strong increase in soil biological activity observed in land-use systems including legumes might partly explain this higher C_p value (Haynes and Mokolobate, 2001; Oberson et al., 2001). The variation in the amount of P_i isotopically exchangeable in one minute (E_1) followed the same trend as the variation in C_p.

Table 3. Parameters of isotopic exchange †

Treatment‡	r_1/R§	c_p ¶ (mg l^{-1})	E_1 # (mg kg^{-1})
SAV	0.02a	0.0015a	0.7a
GL	0.03a	0.002b	0.6a
CR	0.04a	0.003c	0.8a
RGM	0.055b	0.015d	2.7b
F-test	***	***	***

† Values are the average of three replications.
‡ see Table 1.
§ ratio of radioactivity remaining in soil solution to radioactivity added at time 0 after 1 minute of isotopic exchange.
¶ P concentration in the soil solution measured at soil:water ratio 1:10.
# Quantity of P exchangeable within 1 minute.

P Concentrations in Different Fractions of the Sequential Extraction

The positive P balances of the fertilized GL, CR and RGM treatments resulted in significantly higher P concentrations (P<0.001) compared to the savanna soil in all fractions except the organic fractions and residual P (Table 4). This agrees with the results of Friesen et al. (1997) and Oberson et al. (2001), who fractionated P forms according to the same method in the same field experiment, and studies conducted in other tropical soils (Beck and Sanchez, 1994; Linquist et al., 1997). Our results show that

Table 4 Distribution of P in various fractions of the modified Hedley fractionation in different agricultural systems with and without P application on an Oxisol, at three times of incubation after mixing the soils for label application.

Treatment ‡	Incubation Time	resin P_i	Bicarbonate P_i	Bicarbonate P_o	NaOH P_i	NaOH P_o	Hot HCL P_i	Hot HCL P_o	Residual P_t	Total P	Total P_o
		mg kg-1									
SAV	4 hours	0.9 g†	1.4 g	12.4	22 de	46	37 b	6.1 ab	44 ab	172 ef	65
GL	4 hours	2.0 ef	2.8 fg	11.8	27 de	56	34 b	8.6 a	43 b	185 ef	76
CR	4 hours	4.8 d	9.7 def	15.0	102 b	48	56 a	9.1 a	49 ab	298 cd	72
RGM	4 hours	10.0 b	21.4 bc	6.7	100 bc	62	65 a	5.2 abc	47 ab	321 abc	74
SAV	1 week	2.0 ef	4.3 fg	5.7	20 e	42	36 b	4.1 bc	42 b	157 f	52
GL	1 week	2.4 e	6.4 efg	10.0	33 d	47	38 b	3.3 bc	43 ab	184 ef	61
CR	1 week	8.0 c	14.3 cde	14.3	89 c	47	53 a	2.5 bc	50 ab	279 d	64
RGM	1 week	16.4 a	29.8 a	12.8	119 a	40	63 a	3.3 bc	54 ab	338 ab	56
SAV	2 weeks	2.0 ef	4.1 fg	6.3	20 e	42	36 b	4.1 bc	48 ab	164 f	52
GL	2 weeks	4.2 d	6.4 efg	10.3	33 d	49	38 b	2.9 bc	62 a	207 e	62
CR	2 weeks	7.5 c	16.6 cd	11.0	90 bc	56	58 a	1.2 c	61 ab	305 bcd	68
RGM	2 weeks	15.8 a	27.5 ab	15.9	118 a	45	63 a	4.3 bc	62 a	354 a	65
Treatment		***	***	n.s.	***	n.s.	***	**	n.s.	***	n.s.
Time		***	***	n.s.	n.s.	n.s.	n.s.	***	***	*	n.s.

*,**,*** Significant at the 0.05, 0.01, and 0.001 probability level, respectively
† values within a column followed by the same letter do not differ significantly (P=0.05) according to Tukey's test.
‡ see Table 1.

resin-P_i, Bic-P_i and NaOH-P_i increased with P fertilizer input, with the NaOH-P_i fraction being the main sink for the applied P. This P sink function of the NaOH-P_i fraction can be explained by the adsorption of P_i through ligand exchange with hydroxyl groups (Sposito, 1989) located on the surface of Fe and Al (oxy)hydroxides (Ainsworth et al., 1985; Parfitt, 1989; Torrent et al., 1992) and by the desorption of P_i from the surface of (oxy)hydroxides in the presence of 0.5 *M* NaOH (Houmane et al., 1986; Cross and Schlesinger, 1995).

During the continuous 2-week incubation of the soil samples, the resin and the Bic-P_i fractions increased significantly (P<0.05) between the first and second fractionation date for all soils (between 4 and 14 mg kg^{-1} for the sum of resin and Bic-P_i). There was no significant and corresponding decrease in any fraction although total extractable P_o tended to decline (between 8 and 18 mg kg^{-1}) for all soils (Table 5). The absence of significant compensating movements of P out of P_o fractions may be due to the high variability of the results, especially for the organic fractions where coefficients of variation for Bic-P_o were between 13 and 70 % and for NaOH-P_o between 7 and 45 %. Since P_o is determined by the difference between P_t and P_i there are multiple sources of error. High variability of repeated measuring of Bic- and NaOH-P_o were reported in Magid and Nielsen, (1992). Problems in the determination of P_i are mentioned in Tiessen and Moir (1993), especially the possibility that P_i is precipitated along with the organic matter upon acidification and erroneously determined as P_o (P_t-P_i). On the other hand, P_o compounds could be hydrolyzed in the acidic solution during the measurement of P during the colorimetric essay (Condron et al., 1990; Gerke and Jungk, 1991).

Increases in resin and Bic-P_i between 4 hours and 1 week of incubation suggest that mineralization of P_o led to the release of labile P_i from P_o fractions. As the first fractionation was started 4 hours after labeling, the disturbance by mixing the soil with the label and the momentarily increased humidity might additionally have stimulated the microbial activity despite of the preincubation. A temporary stimulation of the microbial activity by the thorough mixing when labeling soil was indicated in microbial turnover studies conducted on soils from the same field experiment (Oberson et al., 2001). This assumption seems likely, as there were little changes in fraction sizes between the second and the third fractionation indicating a stabilization of the system.

Distribution of ^{33}P Among P Fractions and Dynamics over Time

The fraction of ^{33}P recovered in the resin-P_i fraction 4 hours after labeling varied between 22 % in SAV and 60 % in RGM (Figure 1). The ^{33}P recovery in this fraction was positively correlated to the content of total P of the soils (r^2=0.87; P<0.001, 4 h after labeling). The corresponding decrease of ^{33}P in the resin fraction in RGM and CR corresponded with an increase in label recovery in Bic- and NaOH-P_i, while in SAV and GL the decline in resin ^{33}P was accompanied by an increase in ^{33}P in NaOH-P_o (GL also NaOH-P_i), HCl-P_i and residual-P. For SAV and GL, the label recovered in the resin-P_i, and Bic-P_i did not change much between the 1st and the 2nd week and the amount of ^{33}P in NaOH-P_i was stable over the entire incubation time. This shows that in SAV and GL the label was rapidly exchanged between these fractions and that equilibrium with the (labeled) soil solution was reached. In contrast, ^{33}P in the Bic-P_i and the NaOH-P_i of CR and RGM was still increasing after one week while the resin-$^{33}P_i$ continued to decrease, showing that the exchange between these fractions was incomplete.

The data for $^{33}P_o$ were, because of the determination after the separation from Pi with the isobutanol method, not affected by the inherent problems in determination of the P_o fractions in the Hedley fractionation scheme as described previously. Only small amounts of the label were found in organic fractions after 4 hours, but there were already significant differences in NaOH-^{33}Po (P<0.001) in the order: SAV (4%) ≈ GL (2%) > CR (0.4 %) ≈ RGM (0.1 %).

This might be due to differences in microbial activity as observed by Oberson et al. (2001) in the same field experiment. Actually, the microbial biomass in incubated soils, indicated by measured P_{Chl}, C_{Chl} and N_{Chl} values, was significantly different between the soils (Table 5), despite the fact that the samples had been stored in air-dried condition for more than three years before being used in this study. The assumption that recovery of the label in organic fractions was actually due to active processes and not to

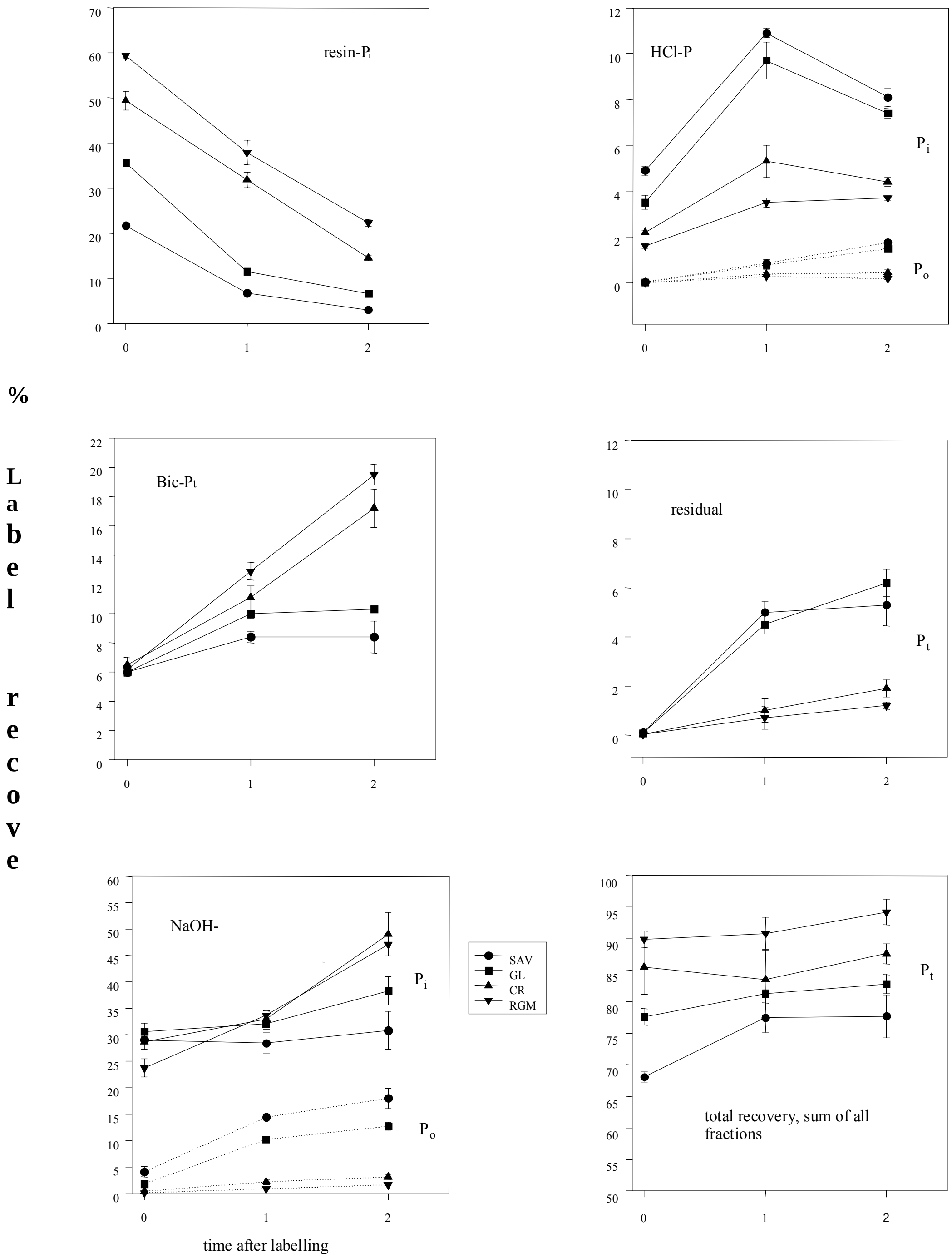


Fig. 1 Percentage of label recovery in the different fractions of the sequential P extraction and in the sum of all fractions at 4 hours, 1 and 2 weeks after labeling soil (Means of three replicates ± SD)

any analytical artifact is supported by the observed increases of NaOH-$^{33}P_o$ and HCl-$^{33}P_o$ for all soils over time. The total recovery of 20 % (SAV) or 14% (GL), respectively, of the label in organic fractions two weeks after labeling shows that these compartments have to be taken into account to understand the fate of P in these very low-P soils (Tiessen et al., 1984; Beck and Sanchez, 1994; Linquist et al, 1997).

Table 5. Size of the soil microbial biomass nutrient pool in different agricultural systems after 20 days of incubation of the formerly air-dried soils. Values are the averages of three replicates†.

treatment ‡	C_{Chl}	N_{Chl}	P_{Chl}
		mg kg^{-1}	
SAV	88.7a	13.7a	1.6a
GL	80.8a	13.5a	1.2ab
CR	72.9a	8.5b	0.7b
RGM	48.2b	6.1b	0.5b
F-Test	**	***	***

,* Significant at the 0.01, and 0.001 probability levels, respectively.
† Means followed by the same letter are not significantly different (P=0.05) by Tukey's multiple range test.
‡ see Table 1.

The proportion of label in the hot HCl and residual P fractions increased significantly with incubation time in all soils. This contradicts the prevailing opinion of recalcitrance of the P in these fractions (Guo and Yost, 1998; Neufeldt et al., 2000). While the total P content in the residual fraction varied significantly with time (Table 4), this was not the case for hot HCl extractable P_i, while hot HCl extractable Po tended to decrease. This suggests that the movement of the label to these fractions was not due to net P-movement but to exchange processes.

Total ^{33}P Label Recovery

At all sampling times during the incubation study, in total between 67 % and 94 % of the applied ^{33}P label could be recovered in the sum of all fractions (Fig. 1). This sum was generally in the order SAV<GL<CR<RGM. These incomplete recoveries can be explained by the fact that the method used to assess total P or residual P was not efficient enough to extract all P. Comparative studies have shown that total P can only be reliably extracted by alkali fusion (Syers et al., 1967; Bowman, 1988), which could not be used in this work. The analysis of soil residues after the acid extraction of residual P (Table 6) indicated indeed that significant amounts of the label remained unextracted, these being higher for SAV and GL than CR and RGM. Although counting of ^{33}P bound to solid phases is generally possible, problems of phase, impurity, self absorption of scintillations by the soil particles or color quenching effects (Gibson, 1980) are difficult to correct, as these influences might be highly variable between samples. However, the recovery of standard additions of ^{33}P to our soil residues was complete and the correlation of the measured radioactivity in the different soil treatment residues with the sample weight was linear (data not shown), thus confirming the qualitative information obtained from the counting of the soil residues.

Altogether the results suggest that the transfer of ^{33}P among the different fractions determined by the sequential extraction was strongly dependent on the degree of saturation of soil Al and Fe (oxy)hydroxides with P_i, and therefore on the bonding energy of P_i to the soil minerals. It is indeed known that a high P_i saturation of metal oxide surfaces causes a more negative charge on the surface and prevents the specific sorption of further P_i ions (Ryden et al., 1977; Bowden et al., 1980). In the P poor soils (SAV and GL), most P_i would be sorbed with such a high energy that their exchangeability would be very limited. A specific sorption of ^{33}P to the surface of Al and Fe (oxy)hydroxides of these soils, although unlikely (Frossard et al., 1994), cannot be excluded (Barrow, 1991). In contrast, in the P rich soils (CR and

RGM), the annual P additions might have resulted in the build up of relatively larger quantities of P_i exchangeable with ^{33}P.

Table 6. Radioactivity measured in soil solid residues by scintillation counting after extraction of residual P by sequential P fractionation starting 1 week after soil labeling

Soil treatment	Bq g^{-1}	soil (decay corrected)†	% of initial label
SAV	2251	(111)	4.4%
GL	1843	(357)	3.6%
CR	427	(215)	0.8%
RGM	348	(140)	0.7%

†Average of three replications, standard error in brackets.
decay corrected to the day of soil labeling.

Specific Activities in the Fractions Determined by the Sequential Extraction

The highest specific activities (SA) observed in this incubation experiment were obtained in the resin extract after 4 hours of incubation (Table 7). This is consistent with the assumption that the amount of P desorbed from the soil by a resin is in very rapid exchange with P_i in the soil solution, as suggested by other studies (Amer et al., 1955; Bowman and Olsen, 1979; Tran et al., 1992; Schneider and Morel, 2000). The subsequent decrease in the SA of resin-P_i reflected the process of isotopic exchange between ^{33}P and stable P_i located on the soil's solid phase (Fardeau, 1996). The order of the SAs in the P_i fractions after 4 hours of incubation followed the extraction sequence (resin-P_i>Bic-P_i>NaOH-P_i>HCl-P_i>residual P), showing that the strongest reactants extracted either large quantities of slowly exchangeable P or a large quantity of P in which only a small part was rapidly exchangeable. After 2 weeks the SAs of resin-P_i, Bic-P_i and NaOH-P_i became closer, suggesting that equilibrium with respect to P transfer between these fractions was being approached. The SAs of resin-P_i, Bic-P_t and NaOH-P_i were not significantly different in SAV and GL while the SA of resin-P_i was still significantly higher than the SA of Bic-P_i and NaOH-P_i in CR and RGM. These observations show that it is not possible to discuss the exchangeability of a certain P fraction without relation to a defined time of exchange (Fardeau et al., 1996).

Although the SAs of the NaOH-P_o and HCl-P_o fraction were relatively low they showed that, depending on land-use, these fractions were connected through active processes with the soil solution, most probably through microbial activity (Oehl et al., 2001). This indicates that the determination of plant available P with short-term isotopic exchange experiments might lead to errors since the dynamics of organic P forms are excluded.

Conclusions

The effect of contrasting land-use systems on the P fractions extracted by the sequential fractionation procedure was assessed in an Oxisol during a 2-week incubation on soils labeled with carrier free ^{33}P. The results show that in the studied Oxisol, the quantities of ^{31}P and ^{33}P recovered in the different fractions were strongly dependent on the total P content of the soil, which was determined by the amount of P added by fertilizers and by plant P uptake.

Table 7. Specific activities ($^{33}P/^{31}P$) in isotopic exchange soil solution and in extracts of the Hedley sequential fractionation in the labeled Oxisols derived from different agricultural systems at different times after labeling. †

Time	treatment	resin P_i	Bic-P_i	NaOH-Pi	NaOH-Po	HCl-Pi	HCl-Po	residual P
		kBq mg P^{-1}						
4 hours	SAV	32.9 AA	5.9 aC	1.8 aD	119 x 10^{-3} aE	180 x 10^{-3} aE	8 x10^{-3} F	3 x10^{-3} aF
	GL	24.5 BA	3.3 bB	1.6 aC	44 x 10^{-3} bE	138 x 10^{-3} bD	3 x10^{-3} F	3 x10^{-3} aF
	CR	13.8 CB	1.3 cC	0.4 bD	11 x 10^{-3} bF	54 x 10^{-3} cE	0	1 x 10^{-3} bF
	RGM	7.9 dA	0.6 cB	0.3 bC	3 x 10^{-3} bE	33 x 10^{-3} dD	0	1 x 10^{-3} bF
	F-test ¶:	***	***	***	***	***	n.s.	***
1 week	SAV	5.1 AbA	2.7 aA	1.9 aB	480 x 10^{-3} aC	430 x 10^{-3} aD	280 x 10^{-3} E	157 x 10^{-3} aF
	GL	6.4 AA	2.2 bB	1.3 bD	293 x 10^{-3} bE	436 x 10^{-3} aE	497 x 10^{-3} DE	140 x 10^{-3} aF
	CR	5.3 AbA	1.1 cC	0.5 cD	64 x 10^{-3} cE	138 x 10^{-3} bE	271 x 10^{-3} DE	26 x 10^{-3} bE
	RGM	3.1 BcA	0.6 cC	0.4 cD	35 x 10^{-3} cE	76 x 10^{-3} bE	159 x 10^{-3} DE	18 x 10^{-3} bE
	F-test:	*	***	***	***	***	n.s.	***
2 weeks	SAV	2.1 ABC	1.6 aB	2.1 aAB	587 x 10^{-3} aC	290 x 10^{-3} aD	566 x 10^{-3} C	154 x 10^{-3} aE
	GL	2.1 B	1.4 aC	1.6 aBC	357 x 10^{-3} bD	249 x 10^{-3} bD	741 x 10^{-3} D	135 x 10^{-3} aE
	CR	2.6 A	1.1 abB	0.7 bB	70 x 10^{-3} cD	99 x 10^{-3} cCD	22 x 10^{-3} D	43 x 10^{-3} bD
	RGM	1.9 A	0.8 bBC	0.5 bC	48 x 10^{-3} cDE	75 x 10^{-3} cD	56 x 10^{-3} DE	26 x 10^{-3} bE
	F-test‡:	n.s.	*	***	***	***	n.s.	***

*,**,*** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

† All values are the average of three replicates. Decay corrected to the day of soil labeling.

‡ ANOVA was calculated separate for each time, means followed by different lower case letters within one column at one time are significantly different (P=0.05) by Tukey's test. The same is valid for means within one row followed by different upper case letters.

In the two soils fertilized annually with P and with a large positive P input-output balance, most of the P_i was stored in the resin-P_i, Bic-P_i and NaOH-P_i fractions. The use of carrier free ^{33}P confirmed that, under all land-use systems studied, these soil P fractions contained most of the exchangeable P and that ^{33}P was transferred from the soil solution first to the resin fraction and then to the Bic-P_i and NaOH-P_i fraction. This suggests that, when this Oxisol is regularly fertilized, P is stored in these three fractions while the plants might take up P from the same fractions. In the two other soils, which had either never been fertilized or had been fertilized only once at the beginning of the field trial, the transfer of ^{33}P in these three fractions (i.e. resin-P_i, Bic-P_i and NaOH-P_i) was less clear, suggesting that the soil P_i was much less exchangeable. In these soils, however, the transfer of ^{33}P into organic P fractions was more important (up to 20 % of the label was found in the organic P fractions two weeks after labeling). As the pool sizes of these organic fractions did not change significantly over time of incubation, the label recovery indicates relatively quick cycling processes, probably mostly of microbial P. In such low P soils, these processes are relevant and should be considered when estimating soil P availability for plants.

Acknowledgements

We thank Dr. P.G. Weidler (ETH Zürich, ITÖ) for the XRD measurements, Mrs Roesch (ETH Institute for Plant Science) for measuring the Al and Fe concentrations and the field staff at CIAT Carimagua research station for taking soil samples. This research was founded by ZIL (Swiss Centre for International Agriculture) and SDC (Swiss Development Cooperation).

References:

Agbenin, J.O., and H. Tiessen. 1995. Phosphorus forms in particle-size fractions of a toposequence from northeast Brazil. Soil Sci. Soc. Am. J. 59:1687-1693.

Ainsworth, C.C., M.E. Sumner, and V.J. Hurst. 1985. Effect of aluminum substitution in Goethite on phosphorus adsorption: I. Adsorption and isotopic exchange. Soil Sci. Soc. Am. J. 49:1142-1149.

Amer, F., D.R. Bouldin, C.A. Black, and F.R. Duke. 1955. Characterization of soil phosphorus by anion exchange resin adsorbtion and P^{32} - equilibration. Plant Soil 4:391-408.

Barrow, N.J. 1991. Testing a mechanistic model. XI. The effects of time and of level of application on isotopically exchangeable phosphate. Journal of Soil Science 42:277-288.

Beck, M.A., and P.A. Sanchez. 1994. Soil phosphorus fraction dynamics during 18 years of cultivation on a typic Paleudult. Soil Sci. 34:1424-1431.

Bowden, J.W., A.M. Posner, and J.P. Quirk. 1980. Adsorption and charging phenomena in variable charge soils, p. 147-166, *In* B. K. G. Theng, ed. Soils with variable charge. New Zealand Society of Soil Science, Lower Hutt.

Bowman, R.A., and C.V. Cole. 1978. An exploratory method for fractionation of organic phosphorus from grassland soils. Soil Sci. 125:95-101.

Bowman, R.A., and S.R. Olsen. 1979. A reevaluation of phosphorus-32 and resin methods in a calcareous soil. Soil Sci. Soc. Am. J. 43:121-124.

Bowman, R.A. 1988. A rapid method to determine total phosphorus in soils. Soil Sci. Soc. Am. J. 52:1301-1304.

Bowman, R.A. 1989. A sequential extraction procedure with concentrated sulfuric acid and dilute base for soil organic phosphorus. Soil Sci. Soc. Am. J. 53:362-366.

Brookes, P.C., D.S. Powlson, and D.S. Jenkinson. 1982. Measurement of microbial biomass phosphorus in soil. Soil Biol. Biochem. 14:319-329.

Chang, S.C., and M.L. Jackson. 1957. Fractionation of soil phosphorus. Soil Sci. 84:133-144.

Condron, L.M., J.O. Moir, H. Tiessen, and J.W.B. Stewart. 1990. Critical evaluation of methods for determining total organic phosphorus in tropical soils. Soil Sci. Soc. Am. J. 54:1261-1266.

Crews, T.E. 1996. The supply of phosphorus from native, inorganic phosphorus pools in continuously cultivated Mexican agroecosystems. Agric. Ecosyst. Environ. 57:197-208.

Cross, F.A., and W.H. Schlesinger. 1995. A literature review and evaluation of the Hedley fractionation: applications to the biogeochemical cycle of soil phosphorus in natural ecosystems. Geoderma 64:197-214.

Daroub, S.H., F.J. Pierce, and B.G. Ellis. 2000. Phosphorus fractions and fate of phosphorus-33 in soils under plowing and no-tillage. Soil Sci. Soc. Am. J. 64:170-176.

Dunbar, A.D., and D.E. Baker. 1965. Use of isotopic dilution in a study of inorganic phosphorus fractions from different soils. Soil Sci. Soc. Am. Proc. 29:259-262.

Fardeau, J.C. 1996. Dynamics of phosphate in soils. An isotopic outlook. Fert. Res. 45:91-100.

Fox, R.L. 1981. External Phosphorus requirements of crops., p. 223-239, *In* R. H. Dowdy, J.A. Ryan, V.V. Volk, D.E. Baker, eds. Chemistry in the Soil Environment, ASA Spec. Publ. No 40. ASA, SSSA, Madison, WI.

Friesen, D.K., and G.J. Blair. 1988. A dual radiotracer study of transformation of organic, inorganic and plant residue phosphorus in soil in presence and absence of plants. Aust. J. Soil Res. 26:355-366.

Friesen, D.K., I.M. Rao, R.J. Thomas, A. Oberson, and J.I. Sanz. 1997. Phosphorus acquisition and cycling in crop pasture systems in low fertility tropical soils. Plant Soil 196:289-294.

Frossard, E., C. Feller, H. Tiessen, J.W.B. Stewart, J.C. Fardeau, and J.L. Morel. 1993. Can an isotopic method allow for the determination of the phosphate-fixing capacity of soils? Commun. Soil Sci. Plant Anal. 24:367-377.

Frossard, E., J.C. Fardeau, M. Brossard, and J.L. Morel. 1994. Soil isotopically exchangeable phosphorus: a comparison between *E* and *L* values. Soil Sci. Soc. Am. J. 58:846-851.

Frossard, E., M. Brossard, M.J. Hedley, and A. Metherell. 1995. Reactions controlling the cycling of P in soils, p. 107-137, *In* H. Tiessen, ed. Phosphorus in the Global Environment. John Wiley & Sons Ltd., Chichester.

Gaviria, S. 1993. Evolution minéralogique et géochimique du fer et de l'aluminium dans les sols ferralitiques hydromorphes des Llanos Orientales de Colombie, Thesis, Université de Nancy I, Nancy.

Gerke, J., and A. Jungk. 1991. Separation of phosphorus bound to organic matrices from inorganic phosphorus in alkaline soil extracts by ultrafiltration. Commun. Soil Sci. Plant Anal. 22:1621-1630.

Gibson, J.A.B. 1980. Modern techniques for measuring the quenching correction in a liquid scintillation counter: a critical review, p. 153-172, *In* C.-T. Peng, et al., eds. Liquid Scintillation Counting, Recent Applications and Development. Academic Press, San Francisco.

Gijsman, A.J., A. Oberson, D.K. Friesen, J.I. Sanz, and R.J. Thomas. 1997. Nutrient cycling through microbial biomass under rice-pasture rotations replacing native savanna. Soil Biol. Biochem. 29:1433-1441.

Guo, F., and R.S. Yost. 1998. Partitioning soil phosphorus into three discrete pools of differing availability. Soil Sci. 163:822-833.

Halpern, A., and G. Stöcklin. 1977. Chemical and biological consequences of b-decay. Part 2. Rad. and Environm. Biophys. 14:257-274.

Haynes, R.J., and M.S. Mokolobate. 2001. Amelioration of Al toxicity and P deficiency in acid soils by addition of organic residues: a critical review of the phenomenon and the mechanisms involved. Nutr. Cycl. Agroecosys. 59:47-63

Hedley, M.J., and J.W.B. Stewart. 1982. Method to measure microbial phosphate in soils. Soil Biol. Biochem. 14:377-385.

Hedley, M.J., W.B. Stewart, and B.S. Chauhan. 1982. Changes in organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. Soil Sci. Soc. Am. J. 46:970-976.

Houmane, B., T. Gallali, and B. Guillet. 1986. Desorption du phosphore fixe sur des oxydes de fer. Science du sol 2:171-181.

Iyamuremye, F., R.P. Dick, and J. Baham. 1996. Organic amendments and phosphorus dynamics: II. Distribution of soil phosphorus fractions. Soil Sci. 161:436-443.

Jayachandran, K., A.P. Schwab, and B.A.D. Hetrick. 1992. Partitioning dissolved inorganic and organic phosphorus using acidified molybdate and isobutanol. Soil Sci. Soc. Am. J. 56:762-765.

Kamprath, E.J., and M.E. Watson. 1980. Conventional soil and tissue tests for assessing the phosphorus status of soils, p. 433-469, *In* F. E. Khasawneh, et al., eds. The Role of Phosphorus in Agriculture. ASA, CSSA, SSSA, Madison, WI.

Lilienfein, J., W. Wilcke, H. Neufeldt, M.A. Ayarza, and W. Zech. 1999. Phosphorus pools in bulk soil and aggregates of differently textured oxisols under different land-use systems in Brazilian *Cerrados*, p. 159-172, *In* R. Thomas and M. A. Ayarza, eds. Sustainable land management for the Oxisols of latin American savannas, Vol. 312. Centro Internacional de Agricultura Tropical, Cali, Colombia.

Linquist, B.A., P.W. Singleton, and K.G. Cassman. 1997. Inorganic and organic phosphorus dynamics during a build-up and decline of available phosphorus in an Ultisol. Soil Sci. 162:254-264.

MacKenzie, A.F. 1962. Inorganic soil phosphorus fractions of some Ontario soils as studied using isotopic exchange and solubility criteria. Can. J. Soil Sci. 42:150-156.

Magid, J., and N.E. Nielsen. 1992. Seasonal variation in organic and inorganic phosphorus fractions of temperate-limate sandy soils. Plant Soil 144:155-165.

Mattingly, G.E.G. 1975. Labile phosphate in soils. Soil Sci. 119:369-375.

McKeague, J.A., and J.H. Day. 1966. Dithionite- and oxalate-extractable Fe and Al as aids in differentiating various classes of soils. Can. J. Soil Sci. 46:13-22

McLaughlin, M.J., A.M. Alston, and J.K. Martin. 1986. Measurement of phosphorus in the soil microbial biomass: a modified procedure for field soils. Soil Biol. Biochem. 18:437-443.

Mehra, O.P., and M.L. Jackson. 1960 Iron oxide removal from soils and clays by a dithionate-citrate system buffered with sodium bicarbonate, p 317-327, *In* Proceedings of the 7th National Conference on Clays and Clay Minerals, 1958, Washington DC.

Murphy, J., and J.P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27:31-36.

Neufeldt, H., J.E. da Silva, M.A. Ayarza, and W. Zech. 2000. Land-use effects on phosphorus fractions in Cerrado oxisols. Bilol Fertil Soils 31:30-37.

Oberson, A., D.K. Friesen, C. Morel, and H. Tiessen. 1997. Determination of phosphorus released by chloroform fumigation from microbial biomass in high P sorbing tropical soils. Soil Biol. Biochem. 29:1579-1583.

Oberson, A., D.K. Friesen, H. Tiessen, C. Morel, and W. Stahel. 1999. Phosphorus status and cycling in native savanna and improved pastures on an acid low-P Colombian Oxisol. Nutr. Cycl. Agroecosys. 55:77-88.

Oberson, A., D. K. Friesen, I.M. Rao, S. Bühler, and E. Frossard. 2001. Phosphorus transformation in an oxisol under contrasting agricultural systems: the role of the soil microbial biomass. Plant Soil, in press.

Oehl, F., A. Oberson, M. Probst, A. Fliessbach, H.-R. Roth, and E. Frossard. 2000. Kinetics of microbial phosphorus uptake in cultivated soils. Biol. Fertil. Soils in press.

O'Halloran, I.P. 1993. Total and organic phosphorus, p. 213-229, *In* M. R. Carter, ed. Soil Sampling and Methods of Analysis. Canadian Society of Soil Science.

Ohno, T., and L.M. Zibilske. 1991. Determination of low concentrations of phosphorus in soil extracts using malachite green. Soil Sci. Soc. Am. J. 55:892-895.

Parfitt, R.L. 1989. Phosphate reactions with natural allophane, ferrihydrite and goethite. J. Soil Sci. 40:359-369.

Ryden, J.C., J.R. McLaughlin, and J.K. Syers. 1977. Mechanisms of phosphate sorption by soils and hydrous ferric oxide gel. J. Soil Sci. 28:72-92

Schneider, A., and C. Morel. 2000. Relationship between the isotopically exchangeable and resin-extractable phosphate of deficient to heavily fertilized soil. Eur. J. Soil Sci. 51:709-715.

Sinaj, S., F. Mächler, E. Frossard, C. Faïsse, A. Oberson, and C. Morel. 1998. Interferences of colloidal particles in the determination of orthophosphate concentrations in soil water extracts. Commun. Soil Sci. Plant Anal. 29:1091-1105.

Sposito, G. 1989. Soil adsorption phenomena, p. 148-161 *In* The Chemistry of Soils. Oxford University Press, New York - Oxford.

Syers, J.K., J.D.H. Williams, A.S. Cambell, and T.W. Walker. 1967. The significance of apatite inclusions in soil phosphorus studies. Soil Sci. Soc. Am. J. 31:752-756.

Thomas, R.L., R.W. Sheard, and J.R. Moyer. 1967. Comparison of conventional and automated procedures for nitrogen, phosphorus and potassium analysis of plant material using a single digestion. Agronomy Journal 59:240-243.

Tiessen, H., J.W.B. Stewart, and C.V. Cole. 1984. Pathways of phosphorus transformations in soils of differing pedogenesis. Soil Sci. Soc. Am. J. 48:853-858.

Tiessen, H., and J.O. Moir. 1993. Characterisation of available P by sequential extraction, p. 75-86, *In* M. R. Carter, ed. Soil Samples and Methods of Analysis. CRC Press Inc. Boca Raton Florida USA.

Tran, T.S., R.R. Simard, and J.C. Fardeau. 1992. A comparison of four resin extractions and ^{32}P isotopic exchange for the assessment of plant available P. Can. J. Soil Sci. 72:281-294.

Vance, E.D., P.C. Brookes, and D.S. Jenkinson. 1987. An extraction method for measuring soil microbial biomass. Soil Biol. Biochem. 19:703-707.

Weidler, P.G., J. Luster, J. Schneider, H. Sticher, and A.U. Gehring. 1998. The Rietveld method applied to the quantitative mineralogical and chemical analysis of a ferralitic soil. European Journal of Soil Science 49:95-105.

Weir, C.C., and R.J. Soper. 1962. Adsorption and exchange studies of phosphorus in some Manitoba soils. Can. J. Soil Sci. 42:31-42.

Journal of Sustainable Agriculture (in press)

Constructing an arable layer through chisel tillage and agropastoral systems in tropical savanna soils of the Llanos of Colombia

S. Phiri[1,2,3], E. Amézquita [2], I.M. Rao[2], and B.R. Singh[1]

[1]Agricultural University of Norway, P.O. Box 5028, NLH, N-1432 Aas, Norway; [2]Centro Internacional de Agricultura Tropical (CIAT), Apartado Aéreo 6713, Cali, Colombia; [3]Misamfu Regional Research Centre, Kasama, Zambia

Abstract

Integration of crop and livestock systems (agropastoralism) is a key strategy for intensifying agricultural production on infertile acid savanna soils, and for reversing problems of soil degradation in the tropics. The main objective of this study was to evaluate the impact of strategies including vertical tillage (1, 2 or 3 passes of chisel), crop rotations (rice-soybean), and agropastoral systems (rice-grass alone pasture; rice-grass/legume pasture) on the build-up of an arable layer and on grain yields of upland rice and soybean. We assessed the build-up of an arable layer in terms of improved soil physical characteristics (bulk density, penetration resistance), soil nutrient availability, soil phosphorus (P) pools, plant growth, and nutrient acquisition during the fourth year after the establishment of different treatments on native savanna soil. The soil used in this study was an Oxisol in the eastern plains (Llanos orientales) of Colombia. Agropastoral treatments (rice-grass alone pasture; rice-grass/legumes pasture) with vertical tillage decreased soil bulk density in the 0-20 cm soil layer by 12% when compared with the unmanaged native savanna. Consistent with bulk density, penetration resistance was also markedly decreased for 0-20 cm depth. Three passes of chisel (rice-soybean rotation) and pasture treatments (grass alone and grass/legume) improved the availability of Bray (II) P, K, Ca, and Mg in the 0-5 cm layer. The biologically available resin-P_i and $NaHCO_3$-P_i each represented 5% of the total P and were significantly affected by chisel down to 10-20 cm depth. The moderately resistant NaOH-P represented, on average, 33% of total P in the 0-20 cm soil layer, and both NaOH-Pi and NaOH-Po were significantly affected by chisel tillage. Results on grain yields of upland rice showed that three passes of chisel could have a negative effect on grain yield, and that yields which declined over time declined more in agropastoral treatments than in rice-soybean rotation. These results indicate that the use of vertical tillage and agropastoral treatments can contribute to the build-up of an arable layer in low fertility savanna soils of the Llanos of Colombia as indicated by improved soil physical properties and nutrient availability. However, to take advantage of the constructed arable layer to improve crop yields, there is a need for developing better crop management strategies to control weeds.

Key words: Acid soils, crop-pasture systems, crop rotations, soil P pools, vertical tillage

Introduction

Tropical savannas cover 45% of the land area in Latin America, or 243 million hectares (Mha), mainly in Brazil (200 Mha), Colombia (20 Mha), and Venezuela (12 Mha). The soils are mainly Oxisols and Ultisols, which are characterized by low nutrient reserves, high acidity (pH 4.0-4.8), high aluminum (Al) saturation (up to 90%), high phosphorus (P) fixing capacity (Sánchez & Logan, 1992), and a low capacity to supply P, K, Mg and S. In addition to soil chemical constraints, these soils also exhibit high bulk density, high resistance to root penetration, low rates of water infiltration, low water holding capacity, and low structural stability (Amézquita, 1998a, b; Phiri et al., 2001a). These chemical and physical constraints have to be alleviated in order to make these infertile soils productive and sustainable for agriculture.

These soils have traditionally been used for extensive cattle ranching on native forage, dominated by *Andropogon* and *Trachypogon* grasses, with low management and almost no purchased inputs (Fisher et al., 1994). Native pasture productivity on these soils is correspondingly low.

Land demand for intensive agricultural production on these soils has increased in the past 20 years. However, intensified agricultural production is usually constrained by poor soil chemical and physical properties. Traditional methods of cultivation by disc harrowing often lead to soil structural deterioration and erosion (Preciado, 1997; White, 1997). Research in the eastern plains (*Llanos Orientales*) of Colombia has shown that these soils are susceptible to physical, chemical, and biological degradation once brought into cultivation (Amézquita, 1998a, b). One of the effects of increasing land preparation is reduction in soil volume due to the decrease in size of soil aggregates. As a consequence, it causes changes in total porosity and pore-size distribution, affecting the flow of water and nutrients. Total porosity, water holding capacity, and macroporosity decline as cultivation is prolonged (McBratney *et al.*, 1992; Preciado, 1997; Amézquita, 1998a). Plowing causes disruption of peds, and this exposes previously inaccessible organic matter to attack by microorganisms while the population of structure-stabilizing fungi and earthworms decrease markedly (White, 1997). These changes result in soil degradation, which reduces water infiltration and increases the loss of soil and plant available nutrients by soil erosion and surface runoff (Amézquita & Londoño, 1997; Amézquita & Molina, 2000).

The practicality of rehabilitating degraded lands depends on the cost relative to the output or environmental benefits expected (Scherr & Yadav, 1996) and their influence on yields. The impact of soil degradation should be assessed in relation to critical limits to crop growth of key soil properties. Identification of appropriate methods of soil restoration is facilitated by knowledge of the key soil properties that influence soil quality and their critical limits in relation to the severity of soil degradation (Lal, 1997).

To achieve improved and sustainable crop and pasture production and to avoid degradation, key soil properties such as soil's physical constraints must be alleviated by appropriate tillage and cropping practices (Amézquita, 1998a; Phiri et al., 2001a). A highly successful strategy for intensifying agricultural production in a sustainable manner and reversing problems of soil degradation involves the integration of crop-pasture systems (agropastoralism) (Vera et al., 1992; Rao et al., 1993; Thomas et al., 1995). This strategy is based on the assumption that a beneficial synergistic effect on production and on soil quality occurs when annual and perennial species are combined in time and space (Spain, 1990; Lal, 1991). Available nutrients are used more efficiently and the chemical, physical and biological properties of the soil are improved.

Phosphorus is among the nutrients that most limits crop production on acid savanna soils (Rao et al., 1999). Studies on P cycling in long-term (16-year-old) introduced pastures in the 'Llanos' of Colombia indicate that legume-based pastures maintain higher organic and available P levels more consistently than grass alone or native pastures (Oberson et al., 1999). Greater turnover of roots and aboveground litter in legume-based pastures could provide steadier organic inputs and, therefore, higher P cycling and availability (Friesen et al., 1997; Rao, 1998; Oberson et al., 1999). Failure of P to enter organic P pools is thought to indicate a degrading system due to low level of P cycling (Friesen et al., 1997; Oberson et al., 2001).

To overcome soil constraints and improve soil quality for agricultural productivity, there is potential for improved soil management through vertical tillage using a chisel plow (Amézquita, 1998a). In this study, we tested the hypothesis that vertical tillage combined with adequate fertilizer inputs to adapted crop and pasture germplasm will improve root growth which could avoid soil compaction and improve root turnover and accumulation of soil organic matter. We also hypothesized that this integration of soil tillage and soil fertility together with vigorous root systems of introduced pasture species could result in the build-up of an arable layer. The arable layer is defined as a surface layer (0-15, 0-25 or 0-30 cm depth depending on cropping system) with minimum soil physical, chemical, or biological constraints.

We believe that the buildup of an arable layer is essential for low fertility acid soils to support sustainable agriculture (Amézquita, 1998b).

The "arable layer" concept proposed here is based on combining: (1) adapted crop and forage germplasm; (2) vertical tillage to overcome soil physical constraints (high bulk density, surface sealing, low porosity and infiltration rates, poor root penetration, etc.); (3) use of chemical amendments (lime and fertilizers) to enhance soil fertility; and (4) use of agropastoral systems to increase rooting, to promote soil biological activity, and to avoid soil compaction after tillage.

The main objective of this study was to evaluate the impact of different strategies of vertical tillage (1, 2, or 3 passes of chisel), crop rotations (rice-soybean), and crop-pasture rotations (rice-grass alone pasture; rice-grass/legume pasture) for 4 years on the buildup of an arable layer. Build-up of the arable layer was assessed in terms of improved soil physical characteristics (bulk density, penetration resistance), soil nutrient availability, soil P pools, plant growth, and nutrient acquisition.

Materials and Methods

As part of a major effort to improve quality of native savanna soils for agricultural production in the Llanos of Colombia, a field experiment was established in May 1996 to determine the impact of vertical tillage, application of soil amendments and fertilizers, crop rotations and crop-pasture rotations on the buildup of an arable layer. The experiment tested two methods: (i) vertical tillage (using chisel) at different intensities (1, 2 and 3 passes) plus crop rotations to improve soil physical conditions in a crop rotation (rice-soybean) system; and (ii) vertical tillage plus use of adapted crop and forage germplasm associations (rice-grass/legumes) to improve soil through vigorous root growth, organic matter accumulation, maintenance of soil structure, and improved soil fertility.

Site description

The experiment was carried out at Matazul farm (4º 9′ 4.9″ N, 72º 38′ 23″ W and 260 m.a.s.l.) located in the Eastern Plains (Llanos) near Puerto Lopez, Colombia. The area has two distinct climatic seasons, a wet season from the beginning of March to December and a dry season from December to the first week of March, and has an annual average temperature of 26.2 ºC. The area has a mean annual rainfall of 2719 mm, potential evapotranspiration of 1623 mm and average relative humidity of 81% (data from the nearby Santa Rosa weather station, located at the Piedmont of the Llanos of Colombia). Before treatment application, the area was under native savanna pasture, consisting for the most part of native savanna grasses. The land is generally flat (slope < 5%), the soil is deep, well structured and has a particle size distribution in the first 10 cm of about 34% clay, 28% silt and 38 % sand (loam texture). The soil has low fertility, particularly low available P because of the soil's high P-fixation capacity. It was classified as Isohyperthermic Kaolinitic Typic Haplustox in the USDA soil classification system (Soil Survey Staff, 1994).

Treatments and experimental design

Use of acid-soil adapted upland rice and tropical forage germplasm in crop-pasture rotations has been demonstrated to be agronomically and economically viable on the infertile acid soils of the South American savannas (Vera et al., 1992; Rao et al., 1993; Thomas et al., 1995). Based on this strategy, the following treatments were designed to buildup an arable layer:

- Upland rice (*Oryza sativa* L. cv. Savanna 6)-soybean (*Glycine max* cv. Soyica Altillanura 2) rotation with 1, 2, or 3 passes of chisel before rice planting in May of each year for 4 years. Soybean was planted in October and harvested in December of each year.
- Rice-grass alone [*Andropogon gayanus* (Ag)] pasture, and rice-grass/legumes [*Pueraria phaseoloides* (Pp) + *Desmodium ovalifolium* (Do)] pasture with two passes of chisel before planting rice and pasture in May each year for 4 years. In both pasture systems, after harvest of rice in September, the pasture was allowed to grow until November. Pasture biomass was incorporated with two passes of

disc harrow in November (end of rainy season) and also before planting rice and grass alone pasture association in May (early rainy season) each year.

- Native savanna was used as a control to compare the impact of the above treatments with the natural (undisturbed) soil conditions.

During the first two years, incidence of weeds in all introduced treatments was low and we did not apply any herbicides to control weed growth. During the next two years, however, we had to apply different herbicides (propanil, glyphosate, or 2,4-D) at recommended rates to control weeds in rice and soybean. The amount of aboveground biomass incorporated was between 3.5 to 4.5 Mg ha^{-1} of grass biomass for grass alone pasture and between 3.0 to 4.0 Mg ha^{-1} of grass biomass and 0.4 to 0.6 Mg ha^{-1} of legume biomass for grass/legumes pasture. Both grass alone and grass/legumes pastures were left ungrazed. We are aware of the fact that the agropastoral treatments in terms of incorporation of pasture biomass every year may neither be economical in short-term nor may reflect the current farmer practices. But we consider this as an important approach for improving soil conditions over a shorter time period than other options.

Vertical tillage was applied in the following sequence: disc harrow, chisel(s), disc harrow to allow good seedbed preparation and sowing with a planting machine. Chisels were applied to a depth of 25 to 30 cm with a distance between chisels of 60 cm. The length of the chisel was 60 cm. Disc harrowing was applied to a depth of 7 to 10 cm with a distance between discs of 12 cm. The diameter of the disc was 60 cm.

Dolomitic lime at a level of 1.5 Mg ha^{-1} to rice-soybean rotation and 0.5 Mg ha^{-1} to rice-pasture associations was applied via broadcast and incorporated with disc harrow one month before planting. Each year, at the time of planting, rice-soybean rotation and rice-pasture associations received (kg ha^{-1}) 80 N (urea), 50 P (TSP), 100 K (KCl), 5 Zn ($ZnSO_4$). Soybean was planted each year after rice with residual soil fertility. Nitrogen and K were split-applied at 4 and 8 weeks for N and 0, 4 and 8 weeks for K after planting rice or rice-pasture associations.

The experiment was laid down in a randomized complete block design with three replications in May, 1996. The individual plot size was 50 x 30 m. A composite soil sample consisting of 50 cores from each plot was collected in a grid pattern. These samples were air-dried, visible plant roots were removed, and soil gently crushed to pass a 2-mm sieve. The <2-mm fraction was used for subsequent chemical analysis. Measurements of soil physical characteristics (bulk density, penetration resistance) were carried out during the fourth year (June 1999) after establishment. Bulk density was determined using the core method and penetration resístanse was measured using a cone penetrometer (DIK-5521, Daiki Rika Kogyo Co., Ltd., Japan) (Amézquita, 1998b). Soil nutrient availability, shoot biomass production, root length, plant nutrient composition, and shoot nutrient uptake were determined for each treatment in September 1999. Soil and plant nutrient analyses and nutrient uptake were determined as described in Rao et al. (1992). Root length was measured using a root length scanner (Rao, 1998). Grain yield of upland rice and soybean were recorded after harvest each year (Sanz et al., 1999). The harvested area for grain yield determination was 2 qudrats of 5 x 5 m^2 in each plot.

Phosphorus fractionation and analysis

A shortened and modified sequential P fractionation as per the method of Tiessen and Moir (1993) was carried out on 0.5-g sieved (<2-mm) soil samples. In brief, a sequence of extractants with increasing strength was applied to subdivide the total soil P into inorganic (P_i) and organic (P_o) fractions (Phiri et al., 2001b). The following fractions were included: (1) Resin P_i, anion exchange resin membranes (used in bicarbonate form) were used to extract freely exchangeable P_i. The remaining P_o in the extract of the resin extraction step was digested with potassium persulfate ($K_2S_2O_8$) (Oberson et al., 1999). (2) Sodium bicarbonate (0.5 *M* $NaHCO_3$, pH = 8.5) was then used to remove labile P_i and P_o sorbed to the soil surface, plus a small amount of microbial P (Bowman and Cole, 1978). (3) Sodium hydroxide (0.1 *M* NaOH) was used next to remove P_i, more strongly bound to Fe and Al compounds (Williams & Walker, 1969) and associated with humic compounds (Bowman & Cole, 1978). (4) The residue containing insoluble P_i and more stable P_o forms (residual P) was digested with perchloric acid ($HClO_4$). To determine total P in the $NaHCO_3$ and NaOH extracts, an aliquot of the extracts was digested with $K_2S_2O_8$ in H_2SO_4 at >150 °C to oxidize organic matter (Bowman, 1989). Organic P was calculated as the difference between total P and P_i in the $NaHCO_3$ and NaOH extracts, respectively. Inorganic P concentrations in all the digests and extracts were measured colorimetrically by the molybdate-ascorbic acid method (Murphy & Riley, 1962). All laboratory analyses were conducted in duplicate, and the results are expressed on an oven-dry basis.

Statistical analysis and data presentation

Analyses of variance were conducted (SAS/STAT, 1990) to determine the significance of the effects of vertical tillage system and crop-pasture rotations on soil and plant parameters. Planned F ratio was calculated as TMS/EMS, where TMS is the treatment mean square and EMS is the error mean square (Mead et al., 1993). Where significant differences occurred, least-significant-difference (LSD) analysis was performed to permit separation of means. Unless otherwise stated, mention of statistical significance refers to $\alpha = 0.05$.

Results and Discussion

Soil physical properties

Bulk density values of different soil layers during the fourth year (June 1999) after establishment of the field experiment are shown in Table 1. Note the high bulk densities in the native savanna that served as a control treatment. Compared with native savanna, bulk density was reduced by the agropastoral and rice-soybean rotations. Consistent to the bulk density values, native savanna soil layers exhibited less total porosity (results not shown), which regulates the entry of water and the flux of air into the profile. Root growth is inhibited when bulk density exceeds 1.4-1.6 Mg m^{-3} and is suppressed at densities near 1.8 Mg m^{-3} (Heilman, 1981; Mitchell et al., 1982). Agropastoral (crop-pasture) treatments, in general, had 16% lower bulk density in the 0-10 cm soil layer and 13% lower in the 10-20 cm soil layer than those of the native savanna. In the subsoil layers, all treatments presented significantly lower values of bulk density than those of native savanna (Table 1). Previous research showed that legume-based pastures contribute to improved quantity and quality of soil organic matter with depth due to vigorous rooting ability of forage components (Fisher et al., 1994; Rao et al., 1994; Rao, 1998). Suitably low bulk densities are of great importance for soil management in this type of soil as they are indicative of factors that regulate root growth, infiltration, and water movement in the soil, which in turn affects nutrient availability in soil and nutrient acquisition by plants (Rao, 1998).`

Results on penetration resistance at different soil layers are shown in Figure 1. In relation to native savanna, all the treatments decreased penetration resistance, particularly in topsoil layers (0-20 cm). These results suggest that it is possible to improve soil physical conditions to enhance water and nutrient availability, which favor rooting of the crop and forage components. The improved soil quality should allow these soils to support greater crop and pasture productivity (Amézquita, 1998b). Lack of additional effects of tillage on rice-soybean rotation compared with rice-pasture treatments (Table 1) indicates that either two passes of the chisel were sufficient in both systems or that deep rooting of introduced pasture species might have contributed biological tillage to improve soil quality. Both tillage and agropastoral treatments improved soil conditions, but whether one treatment is more beneficial than another over a longer period needs to be evaluated further.

Soil chemical properties

Soil chemical characteristics and root length distribution for different soil layers during the fourth year (September 1999) are shown in Table 2. As expected, compared to native savanna where nutrient availability was low and Al levels high, the different crop rotation and agropastoral treatments improved nutrient availability and reduced Al levels. The higher rate of dolomitic lime application (1.5 Mg ha^{-1}) to rice-soybean rotation reduced the exchangeable Al level and increased the exchangeable Ca and Mg levels in comparison with the agropastoral treatments (0.5 Mg ha^{-1}). Exchangeable Al levels decreased in the first two layers, but remained at similar values of native savanna below these depths.

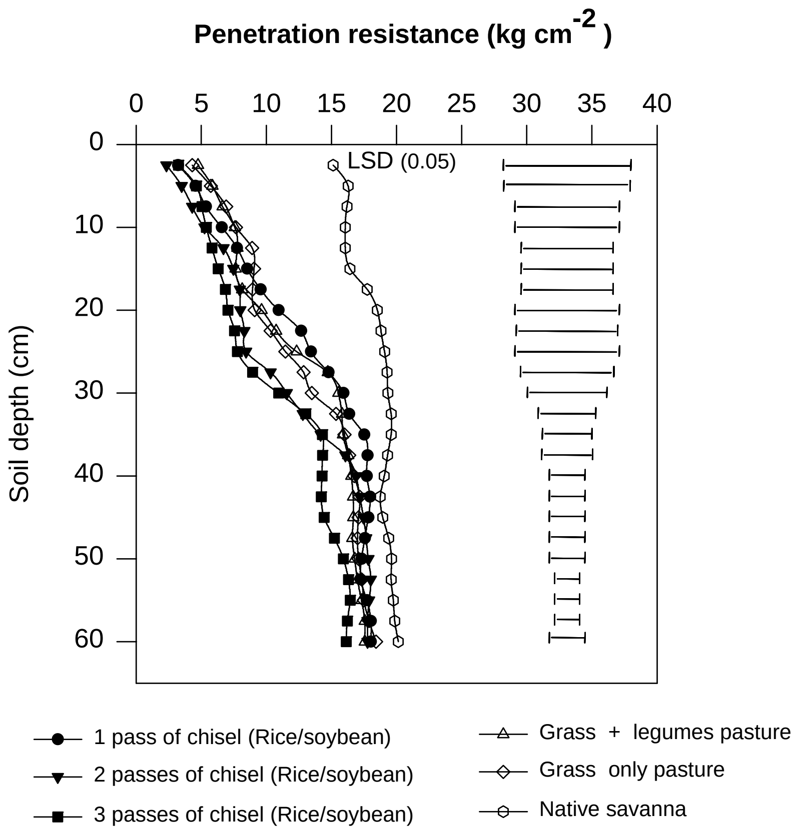


Figure 1. Penetration resistance (measured at field capacity) with soil depth during the fourth year (June 1999) after establishment of different tillage and agropastoral treatments. LSD values are at 0.05 probability level.

Differences in available P between rice-soybean rotations and agropastoral treatments were probably the result of differences in the rate of lime applied, which may have affected P sorption in soil. Other nutrients, such as K, Ca and Mg, accumulated in the topsoil. Nutrient values tended to be greater in the 0-5 cm layer as compared to subsoil layers. Available K was 2 to 4 times greater than that of native savanna (0.09 cmol$_c$ kg^{-1}). Availability of Ca and Mg was 4 to 10 times higher than that of native savanna. These results suggest that application of lime and fertilizer could markedly improve soil fertility, particularly in topsoil. Chisel treatments were moderately effective to incorporate lime and P to deeper layers. Total C and total root length across the soil profile up to 40 cm soil depth were greater in agropastoral (rice-grass/legumes) treatment than those of rice with vertical tillage.

P fractionation

To simplify interpretation of results, the P fractions were divided into three groups using a criterion similar to that given by Bowman and Cole (1978) and by Tiessen et al. (1984). The three groups were: (1) biologically available P, (2) moderately resistant P, and (3) sparingly available P.

Table 1. Bulk density (Mg m^{-3}) of soils in profiles during the fourth year (June 1999) after establishment of different rice/soybean rotation and agropastoral systems compared with native savanna. LSD values are at 0.05 probability level.

Soil depth (cm)	System						LSD (0.05)
	Rice/soybean rotation			Rice + pastures (Agropastoral)		Native savanna (control)	
	1 pass of chisel	2 passes of chisel	3 passes of chisel	Grass only (Ag)	Grass + legumes (Ag + Pp + Do)	Savanna	
0-5	1.36	1.36	1.33	1.37	1.38	1.61	0.11
5-10	1.49	1.42	1.46	1.44	1.39	1.64	0.09
10-20	1.54	1.57	1.50	1.55	1.56	1.73	0.08
20-40	1.60	1.60	1.57	1.56	1.62	1.73	0.06
LSD (0.05)	0.16	0.18	0.16	0.15	0.19	0.09	

Ag = *Andropogon gayanus;* Pp = *Pueraria phaseoloides;* Do = *Desmodium ovalifolium*.

Biologically available P (H_2O-P_o, resin-P_i, and $NaHCO_3$-P_i, and -P_o) is available or becomes available to plants in a short time (from days to a few weeks) (Cross and Schlesinger, 1995). The resin and the bicarbonate P_i consists of labile P_i and represents soil solution P, soluble phosphates originating from calcium phosphates, and weakly adsorbed P_i on the surfaces of sesquioxides or carbonates (Mattingly, 1975).

The H_2O-P_o and bicarbonate-P_o are considered "readily mineralizable" and related to P uptake by plants (Fixen & Grove, 1990). This P_o fraction includes nucleic acid-P, sugar-P, lipid-P, phytins, and other high-molecular-weight P compounds (Bowman & Cole, 1978). The "readily mineralizable" H_2O-P_o represented, on average, 1% of the total soil P and was uniformly distributed throughout the profile and across the tillage systems (Figure 2A). The resin and the bicarbonate P_i, on average, represented 4 and 6%, respectively, of the total soil P in the 0-5 and 0-10 cm soil depths. The profile distribution of these fractions is shown in Figure 2B, C. These fractions decreased rapidly with increasing soil depth and were affected by the tillage system employed up to the 10-20 cm soil depth. The highest values were obtained in the agropastoral treatments followed by the three-chisel-passes treatment to crop-rotation.

The $NaHCO_3$-P_o represented about 2.5 % of the total soil P and did not differ much with increasing soil depth (Figure 2D). For the most part, there were no treatment effects and a gradual decline was observed with increasing soil depth. On average, the "biologically available" P represented 11-15% and 7-10% of the total soil P in the 0-20 and 20-40 cm soil layers, respectively. These results indicate that agropastoral treatments and 3 passes of chisel to crop rotation increased biologically active P_i but had little effect on P_o. It is also important to note that the effects on biologically available P fractions were not significant below 20 cm soil depth except for $NaHCO_3$-P_i.

Moderately resistant P includes the NaOH-P_o and NaOH-P_i fractions that are not immediately available to plants, but have the potential to become available in a medium term (from months to a few years) through biological and physico-chemical transformations (Cross & Schlesinger, 1995). This fraction is thought to be associated with humic compounds, and amorphous and some crystalline Al- and Fe-phosphates (Bowman & Cole, 1978). The moderately resistant P fraction represented 30-35% and 20-25% of the total soil P in the 0-20 and 20-40 cm soil layers, respectively. The large amount of P recovered from this fraction can be attributed to the high contents of Al- and Fe-oxides associated with Oxisols. Both the NaOH-P_i and the NaOH-P_o were affected by treatments (Figure 3A, B). The greatest effect was

Table 2. Chemical characteristics of soil layers and total root length distribution during the fourth year (September 1999) after establishment of different agropastoral treatments. Root length values are for upland rice in the case of rice/soybean rotation and upland rice + pastures in the case of agropastoral systems. LSD values are at 0.05 probability level.

Soil/plant parameters	Soil depth (cm)	System: Rice/soybean rotation			Rice + pastures (Agropastoral)		Native savanna (control)	LSD (0.05)
		1 pass of chisel	2 passes of chisel	3 passes of chisel	Grass only (Ag)	Grass + legumes (Ag + Pp + Do)	Savanna	
PH	0-5	5.7	5.8	5.7	5.1	5.1	4.6	0.49
	5-10	5.7	5.9	5.5	5.0	5.0	4.6	0.52
	10-20	5.1	5.3	5.1	4.8	4.8	4.7	0.24
	20-40	4.9	5.0	4.9	4.8	4.8	4.8	0.08
	LSD (0.05)	0.7	0.7	0.6	0.2	0.2	0.2	
C (g kg^{-1})	0-5	20.1	18.3	21.3	19.9	21.7	16.3	2.11
	5-10	18.4	18.3	20.4	19.1	21.8	10.9	3.98
	10-20	15.0	15.5	17.3	14.9	17.6	6.7	4.19
	20-40	12.8	12.3	13.8	13.2	13.7	3.7	4.11
	LSD (0.05)	5.2	4.5	5.4	5.1	6.2	8.7	
P (mg kg^{-1})	0-5	34.8	34.6	46.2	19.6	15.1	3.7	16.36
	5-10	20.7	15.5	16.9	7.2	4.6	2.0	7.92
	10-20	3.2	4.5	1.6	2.4	1.2	1.4	1.33
	20-40	1.8	1.5	1.0	1.5	0.6	1.1	0.45
	LSD (0.05)	24.9	23.8	33.7	13.3	10.7	1.8	
K ($cmol_c$ kg^{-1})	0-5	0.20	0.33	0.24	0.17	0.24	0.09	0.08
	5-10	0.12	0.14	0.15	0.09	0.10	0.05	0.03
	10-20	0.07	0.02	0.07	0.06	0.06	0.04	0.02
	20-40	0.05	0.04	0.06	0.04	0.04	0.02	0.01
	LSD (0.05)	0.11	0.23	0.13	0.09	0.14	0.05	
Ca ($cmol_c$ kg^{-1})	0-5	2.23	1.69	1.72	0.66	0.77	0.15	0.83
	5-10	1.54	1.37	1.41	0.43	0.60	0.12	0.63
	10-20	0.54	0.60	0.21	0.21	0.19	0.11	0.21
	20-40	0.19	0.13	0.18	0.13	0.09	0.11	0.04
	LSD (0.05)	1.48	1.13	1.27	0.38	0.52	0.03	
Mg ($cmol_c$ kg^{-1})	0-5	0.95	0.76	0.75	0.29	0.37	0.08	0.35
	5-10	0.68	0.68	0.67	0.19	0.30	0.06	0.29
	10-20	0.34	0.36	0.16	0.13	0.13	0.05	0.13
	20-40	0.14	0.12	0.12	0.08	0.06	0.04	0.04
	LSD (0.05)	0.57	0.47	0.53	0.14	0.23	0.03	
Al ($cmol_c$ kg^{-1})	0-5	0.43	0.31	0.37	1.25	1.09	1.98	0.69
	5-10	0.62	0.31	0.42	1.56	1.35	1.93	0.70
	10-20	1.35	0.94	1.25	1.56	1.25	1.69	0.27
	20-40	1.46	1.25	1.25	1.56	1.14	1.25	0.16
	LSD (0.05)	0.82	0.75	0.79	0.25	0.18	0.53	
Root length (km m^{-2})	0-5	1.7	2.9	2.0	2.2	3.4	1.8	0.70
	5-10	0.6	2.4	1.2	1.8	2.6	1.2	0.81
	10-20	0.9	1.4	1.3	2.0	2.4	0.8	0.65
	20-40	0.8	1.8	1.2	1.5	2.1	0.4	0.66
	LSD (0.05)	0.8	1.1	0.6	0.5	0.9	1.0	

Ag = *Andropogon gayanus*, Pp = *Pueraria phaseoloides;* Do = *Desmodium ovalifolium.*

observed with the three chisel passes with crop rotation and the grass/legumes pasture treatments. The greater P_o contribution to the NaOH fraction by agropastoral systems, the two-chisel-passes and the three-chisel passes with crop rotation could be highly desirable because the NaOH-P_o fraction is usually more stable than $NaOHCO_3$-P_o and may represent a relatively active pool of P in tropical soils under cultivation, especially those not receiving mineral P fertilizers (Tiessen et al., 1992). These results indicate that vertical tillage with three-chisel-passes with crop-rotation and two-chisel-passes with grass/legumes pasture treatments can markedly improve P availability through moderately resistant P pools.

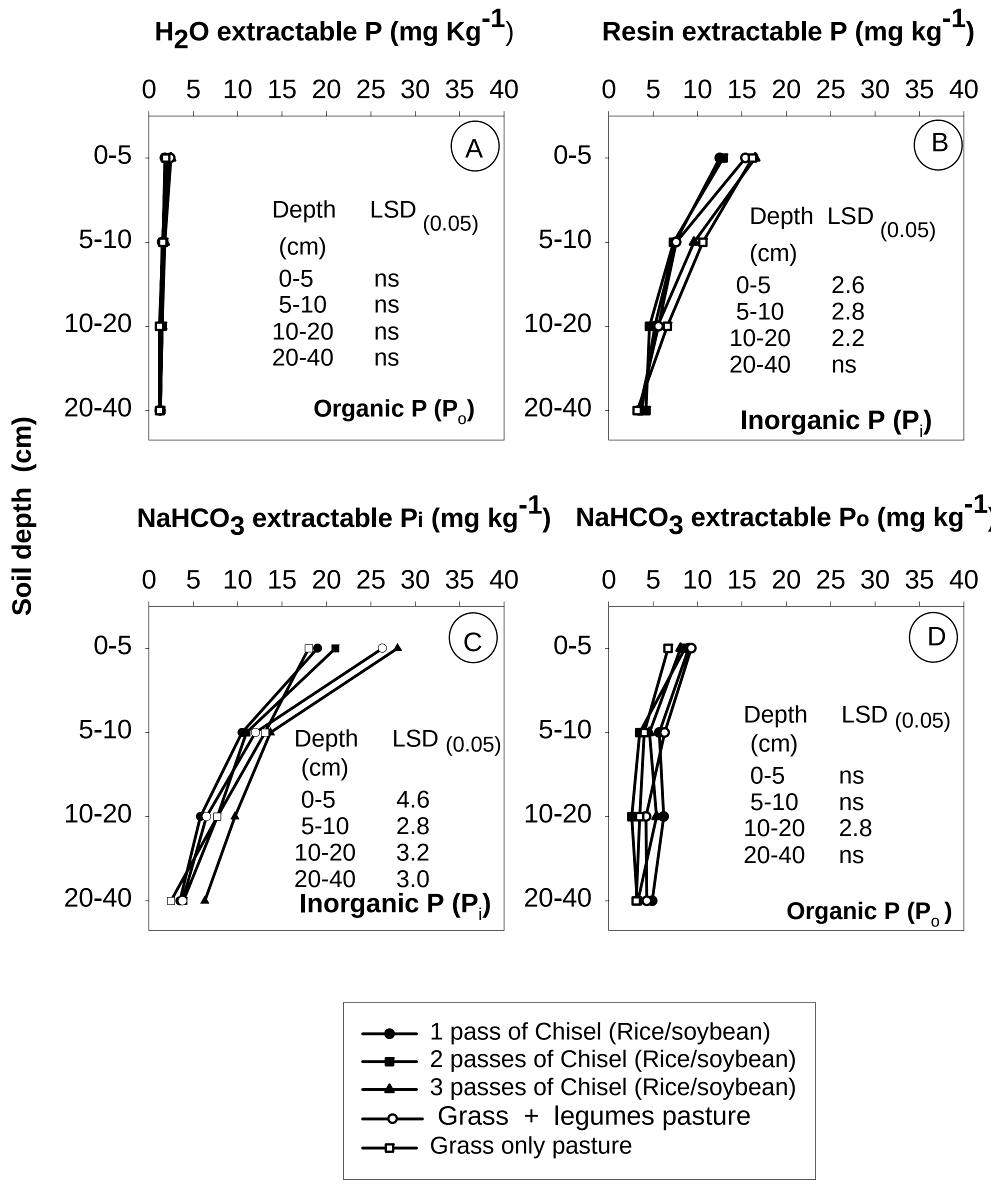


Figure 2. Distribution of the biologically available P fractions in soil profiles during the fourth year (September 1999) after establishment of different tillage and agropastoral treatments. Biologically available P fractions in 0 to 10 cm soil depth in native savanna plots were 7.1, 3.3, 7.1 and 5.4 mg kg^{-1} for H_2O-P_o, resin-P_i, and $NaHCO_3$-P_i, and $NaHCO_3$-P_o, respectively. LSD values are at 0.05 probability level; ns = not significant.

The *sparingly available P* includes the HCl-P (not done in this study) and the Hedley et al. (1982) residual-P. The sparingly available P is not available on a short time scale such as one or more crop cycles, but a small fraction of this pool may become available during long-term soil P transformations. In general, this fraction was slightly affected by tillage system in the top 0-5 cm soil layer (Figure 4A) and then remained fairly consistent through the rest of the soil profile. However, it represented about 49% and 73% of the total P in 0-20 and 20-40 cm soil layers, respectively. This fraction is mainly composed of the stable humus fraction and highly insoluble P_i forms (Hedley et al., 1982) and was not affected by chisel, crop rotation and agropastoral treatments in the short-term.

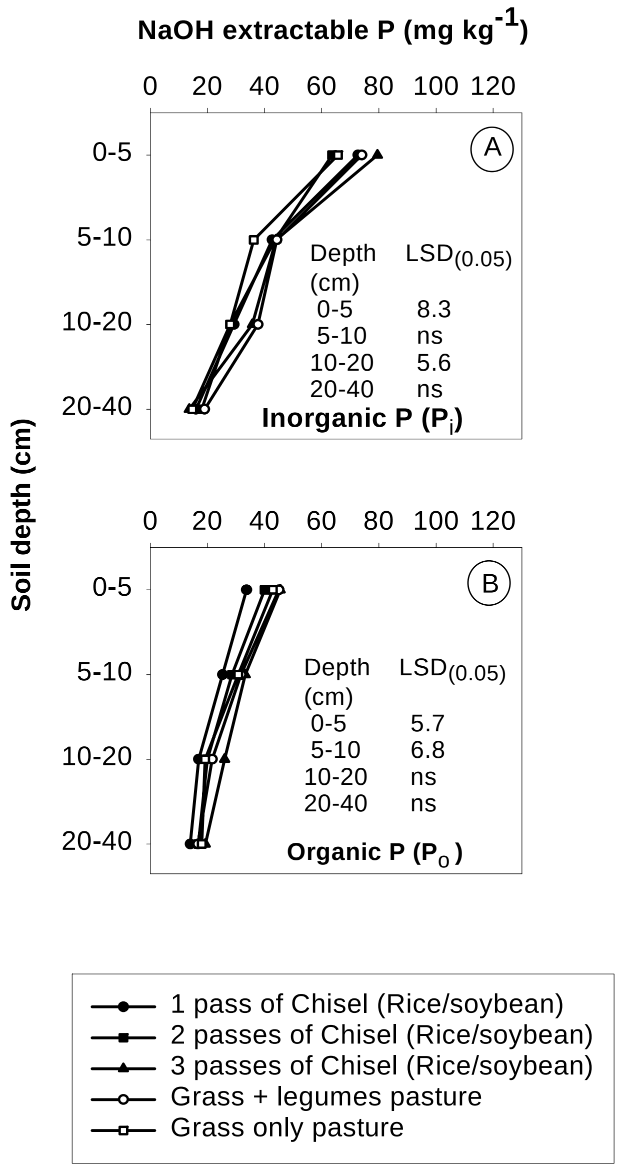


Figure 3. Distribution of the moderately resistant P fractions in soil profiles during the fourth year (September 1999) after establishment of different tillage and agropastoral treatments. Moderately resistant P fractions in 0 to 10 cm soil depth in native savanna plots were 16.1 and 25.5 mg kg^{-1} for NaOH-P_i and NaOH-P_o, respectively. LSD values are at 0.05 probability level; ns = not significant.

We also looked at the sum of the soil Po fraction (H_2O-P_o + $NaHCO_3$-P_o + NaOH-P_o) to detect any significant effects of treatments on P_o that were not evident in the individual fractions. The sum of the soil P_o fraction was, on average, 16% of the total P in the top 0-5 cm soil layer and decreased steadily to an average of 13.5% at the 20-40 cm soil layer (Figure 4B). The greatest amounts were obtained in the agropastoral systems, and the two-passes-of-chisel and three-passes-of-chisel treatments of crop rotation. The one-chisel pass treatment with crop rotation had the lowest effect on this fraction. Oxisols have high P-sorbing capacity resulting from their high Al and Fe content. Therefore, the increase of total P_o resulting from treatment effects is desirable because the P maintained in organic pools may be better protected from loss through fixation than P flowing through inorganic pools in soil. Adsorption of P occurs mainly through processes in the soil, and as such minimizing P interaction with the soil is an important management tool for increasing P cycling.

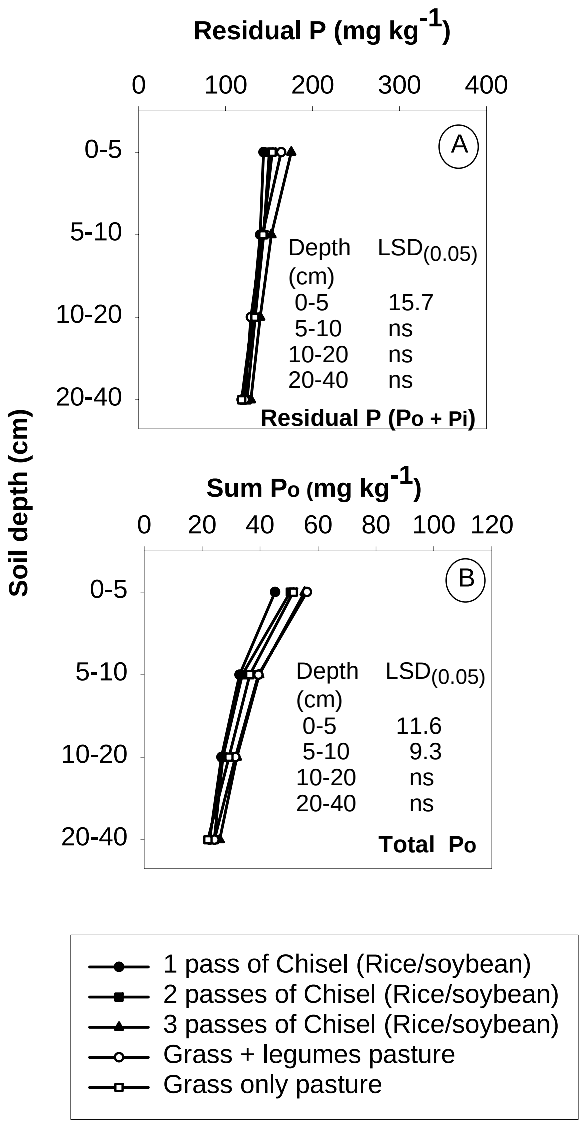


Figure 4. Distribution of the residual P and sum of soil Po in soil profiles at four years after establishment of different tillage and agropastoral treatments. Residual and sum of soil Po fractions in 0 to 10 cm soil depth in native savanna plots were 144 and 38.0 mg kg^{-1} for residual P and total P_o, respectively. LSD values are at 0.05 probability level; ns = not significant.

Crop yield, plant growth and total nutrient acquisition
The trend in rice and soybean grain yields as a function of time is shown in Table 3. It was not possible to maintain yields of either crop in any of the treatments used. During the first year, yields of rice and soybean were relatively high, but they declined with time irrespective of the treatment, with the steepest rate of decline being recorded in the rice-pasture systems. The yield decline with rice may have been due to increase in weed biomass, which had a trend of 35, 320 and 704 kg ha^{-1} for the years 1996, 1997 and 1998, respectively, in rice crop across treatments. Soybean was relatively less affected by weeds and it failed to produce any grain during 1998 due to severe drought conditions. Shoot biomass of rice was less when associated with pasture components than under chisel treatments with crop rotation (Table 4). This could be mainly due to the competition of pasture components for nutrients, water and light. These results indicate that decrease in rice yields was much greater in agropastoral treatments than in rice-soybean rotation. On average, an increase in the number of chisel passes from 1 to 3 did not significantly affect rice biomass or grain yield production. Amézquita (1998a) reported that three passes could be excessive for these soils causing a collapse of soil volume.

Shoot biomass of rice was greater with rice-soybean rotation than with rice/pasture treatments (Table 4). This was mainly due to the competition of pasture components for nutrients, particularly K and Ca which showed greater uptake in rice/pasture treatments than in rice-soybean rotation (Table 4). Previous research showed that pasture legumes could be of great importance in stimulating soil biological activity, nutrient cycling and addition of organic matter to the soil, which have beneficial effects on the production system (Rao et al., 1994; Thomas et al., 1995; Fisher et al., 1999; Sanz et al., 1999). Rao (1998) reported that the deep root systems of improved tropical forages are efficient in extracting nutrients from subsoil and recycling them throughout the plant and back to the soil through the death of plant tissue. Legumes also improve nutrient cycling and the nutritive value of forage. The agropastoral systems had greater root length compared to 1 pass of chisel treatment, particularly in the subsoil layers (Table 2). This is desirable as the turnover of roots through time contributes not only to nutrient cycling but also to soil improvement via positive changes in soil porosity and carbon sequestration in soil (Aerts et al., 1992; Rao et al., 1993; van de Geijn & van Veen, 1993; Veldkamp 1993; Cadisch et al., 1994; Fisher et al., 1994; Rao 1998).

Conclusions

This study indicated that vertical tillage with 2 chisel passes for rice/soybean rotation or agropastoral treatments improved soil physical and chemical characteristics. However, these improved soil conditions did not translate into improved and sustained grain yields of either upland rice or soybean. This might have occurred because of crop management, particularly with the increase in incidence of weeds over time. Further research work is needed to develop appropriate crop management to benefit from the improved soil conditions. Buildup of an arable layer requires improvement of soil physical, chemical and biological conditions. Introduction of tropical pasture components with legumes into the production system could provide adequate soil physical conditions, to improve nutrient acquisition and recycling, and to facilitate accumulation of better quality and quantity of soil organic matter leading to the buildup of an arable layer. This study provides experimental evidence to promote the concept of building-up an arable layer in tropical Oxisols using vertical tillage and agropastoral treatments. But to improve and sustain crop production on infertile Oxisols of the tropics, there is a need to develop better crop management strategies to overcome weed problems. We suggest that the buildup of an arable layer is a prerequisite to move towards no-till or direct drilling systems to minimize environmental degradation in savanna soils of the Llanos of Colombia.

Table 3. Rice and soybean grain yield (kg ha^{-1}) as a function of time. LSD values are at 0.05 probability level.

System	Treatment	Rice 1996	Rice 1997	Rice 1998	Rice 1999	LSD (0.05)	Soybean 1996	Soybean 1997	Soybean 1998	Soybean 1999	LSD (0.05)
Rice-soybean rotation	1 pass of chisel	3240	2760	2064	1219	1398	1930	1330	-	1273	ns
	2 passes of chisel	3650	2890	1720	1447	1636	1830	1280	-	1272	ns
	3 passes of chisel	3310	3080	1455	1147	1757	1830	1260	-	1315	ns
Rice + pastures (Agropastoral)	Grass only (A.g.)	3180	1730	422	374	2111	-	-	-	-	
	Grass + legumes (Ag + Pp + Do)	3300	1760	724	736	1933	-	-	-	-	
LSD (0.05)		227	805	852	530		ns	ns	-	ns	

Ag = *Andropogon gayanus;* Pp = *Pueraria phaseoloides;* Do = *Desmodium ovalifolium*.
ns = not significant.

Table 4. Plant growth and total nutrient acquisition by different crop rotation and agropastoral systems during the fourth year (September 1999) after establishment of different treatments. Values of shoot nutrient uptake are for upland rice only in the caseof rice/soybean rotation and for upland rice + pasture species in the case of agropastoral treatments. LSD values are at 0.05 probability level.

Systems	Treatments	Shoot biomass		Shoot nutrient uptake				
		Rice	Pasture	N	P	K	Ca	Mg
		($kg\ ha^{-1}$)						
Rice/soybean rotation	1 pass of chisel	3990	-	41	7.2	39.7	6.1	7.3
	2 passes of chisel	4210	-	50	8.0	42.9	7.2	8.1
	3 passes of chisel	4370	-	50	7.3	42.8	6.6	7.7
Rice+pastures (Agropastoral)	Grass only (Ag)	2280	2120	54	6.6	66.3	10.3	7.7
	Grass + legumes (Ag + Pp + Do)	2420	3140	65	7.7	71.6	12.9	8.6
LSD (0.05)		1480	ns	ns	ns	26.0	3.4	ns

Ag = *Andropogon gayanus;* Pp = *Pueraria phaseoloides;* Do = *Desmodium ovalifolium*.
ns = not significant.

References

Aerts, R., C. Bakker, & H. de Caluwe. 1992. Root turnover as determinant of the cycling of C, N, and P in a dry heathland ecosystem. Biogeochemistry 15: 175-190.

Amézquita, E. 1998a. Propiedades físicas de los suelos de los Llanos Orientales y sus requerimientos de labranza. *In* G. Romero, D. Aristizábal & C. Jaramillo (eds) Memorias "Encuentro Nacional de Labranza de Conservación". 28-30 de Abril de 1998. Villavicencio-Meta, Colombia.

Amézquita, E. 1998b. Hacia la sostenibilidad de los suelos de los Llanos Orientales. *In* Memorias "Manejo de Suelos e Impacto Ambiental". IX Congreso Colombiano de la Ciencia del Suelo, Paipa, Octubre 21-24 de 1998. pp 106-120. Sociedad Colombiana de la Ciencia del Suelo, Bogotá, Colombia.

Amézquita, E. & H. Londoño. 1997. La infiltración del agua en algunos suelos de los Llanos Orientales y sus implicaciones en su uso y manejo. Rev. Suelos Ecuatoriales 27: 163-169.

Amézquita, E. & D. Molina. 2000. Un método de campo para evaluar escorrentía, erosión y agua percolada en la Altillanura Colombiana. X Congreso Nacional de la Ciencia del Suelo, Octubre 11 a 13, 2000. Medellin, Colombia.

Bowman, R. A. 1989. A sequential extraction procedure with concentrated sulfuric acid and dilute base for soil organic phosphorus. Soil Sci. Soc. Am. J. 53: 362-366.

Bowman, R. A. & C. V. Cole. 1978. An exploratory method for fractionation of organic phosphorus from grassland soils. Soil Sci. 125: 95-101.

Cadisch, G., K. E. Giller, S. Uriquiaga, C. H. B. Miranda, R. M. Boddey, & R. M. Schunke. 1994. Does phosphorus supply enhance soil-N mineralization in Brazilian pastures? Eur. J. Agron. 3: 339-345.

Cross, A. F. & W. H. Schlesinger. 1995. A literature review and evaluation of the Hedley fractionation: application to the biogeochemical cycle of soil phosphorus in natural ecosystems. Geoderma 67: 197-214.

Fisher, M. J., I. M. Rao, M. A. Ayarza, C. E. Lascano, J. I. Sanz, R. J. Thomas, & R. R. Vera. 1994. Carbon storage by introduced deep-rooted grasses in the South American savannahs. Nature (Lond.) 371: 236-238.

Fisher, M. J., I. M. Rao, & R. J. Thomas. 1999. Nutrient cycling in tropical pastures, with special reference to neotropical savannas. *In* Proceedings of the XVIII International Grassland Congress (Vol. 3). pp 371-382. Winnipeg and Saskatoon, Canada.

Fixen, P. E. & J. H. Grove. 1990. Testing soils for phosphorus. *In* R. L. Westerman (ed) Soil Testing and Plant Analysis. pp 141-180. SSSA, Madison, WI.

Friesen, D. K., I. M. Rao, R. J. Thomas, A. Oberson, & J. I. Sanz. 1997. Phosphorus acquisition and cycling in crop and pasture systems in low fertility tropical soils. Plant and Soil 196: 289-294.

Hedley, M. J., R. E. White, & P. H. Nye. 1982. Plant-induced changes in the rhizosphere of rape (*Brassica napus* var. emerald) seedlings. III. Changes in L value, soil phosphate fractions and phosphatase activity. New Phytol. 91: 45-56.

Heilman, P. 1981. Root penetration of Douglas-fir seedlings into compacted soil. Forest Sci. 27: 660-666.

Lal, R. 1991. Tillage and agricultural sustainability. Soil Tillage Research. 20: 133-146.

Lal, R. 1997. Soil quality and sustainability. *In* R. Lal, W. H. Blum, C. Valentine, & B. A. Stewart (eds). Methods for Assessment of Soil Degradation. Advances in Soil Science. pp 17-30. CRC, Boca Raton, N.Y.

Mattingly, G. E. G. 1975. Labile phosphate in soils. Soil Sci. 119: 369-375.

McBratney, A. B., C. J. Moran, J. B. Stewart, S. R. Cattle, & A. J. Koppi. 1992. Modifications to a method of rapid assessment of soil macropore structure by image analysis. Geoderma. 53: 255-274.

Mead, R., R. N. Curnow, & A. M. Hasted. 1993. Statistical Methods in Agriculture and Experimental Biology. Chapman and Hall, London.

Mitchell, M. L., A. E. Hassan, C. B. Davey & J. D. Gregory. 1982. Loblolly pine growth in compacted greenhouse soils. Trans. ASAE 25: 304-307.

Murphy, J. & P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Analy. Chimica Acta 27: 31-36.

Oberson, A., D. K. Friesen, H. Tiessen, C. Morel, & W. Stahel. 1999. Phosphorus status and cycling in native savanna and improved pastures on an acid low-P Colombian soil. Nutr. Cycl. Agroecosystems 55: 77-88.

Oberson, A., D. K. Friesen, I. M. Rao, S. Buehler, & E. Frossard. 2001. Phosphorus transformations in an oxisol under contrasting land-use systems: The role of the soil microbial biomass. Plant and Soil 237: 197-210.

Phiri, S., E. Amezquita, I. M. Rao, & B. R. Singh. 2001a. Disc harrowing intensity and its impact on soil properties and plant growth of agropastoral systems in the Llanos of Colombia. Soil and Tillage Res. 62: 131-143.

Phiri, S., E. Barrios, I. M. Rao, & B. R. Singh. 2001b. Changes in soil organic matter and phosphorus fractions under planted fallows and a crop rotation on a Colombian volcanic-ash soil. Plant and Soil 231: 211-223.

Preciado, L. G. 1997. Influencia del tiempo de uso del suelo en las propiedades físicas, en la productividad y sostenibilidad del cultivo de arroz en Casanare. Tesis de Maestría. Universidad Nacional de Colombia, Sede Palmira.

Rao, I. M. 1998. Root distribution and production in native and introduced pastures in the South America savannas. *In* J. E. Box Jr. (ed) Root Demographics and Their Efficiencies in Sustainable Agriculture, Grasslands, and Forest Ecosystems. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 19-42.

Rao, I. M., W. Roca, M. A. Ayarza, E. Tabares, & R. Garcia. 1992. Somaclonal variation in plant adaptation to acid soil in the tropical forage legume *Stylosanthes guianesis*. Plant Soil 146: 21-30.

Rao, I. M., R. S. Zeigler, R. Vera, & S. Sarkarung. 1993. Selection and breeding for acid-soil tolerance in crops: upland rice and tropical forages as case studies. BioScience 43: 454-465.

Rao, I. M., M. A. Ayarza, & R. J. Thomas. 1994. The use of carbon isotope ratios to evaluate legume contribution to soil enhancement in tropical pastures. Plant and Soil 162: 177-182.

Rao, I. M., D. K. Friesen, & M. Osaki. 1999. Plant adaptation to phosphorus-limited tropical soils. *In* M. Pessarakli (ed) Handbook of Plant and Crop Stress. pp. 61-96. Marcel Dekker, Inc., New York, USA.

Sánchez, P. A. & T. J. Logan. 1992. Myths and science about the chemistry and fertility of soils in the tropics. *In* R. Lal & P. A. Sánchez (eds) Myths and science of soils in the tropics. pp 35-46. SSSA Spec. Publ. 29. SSSA, Madison, WI.

Sanz, J. I., R. S. Zeigler, S. Sarkarung, D. L. Molina, & M. Rivera. 1999. Sistemas mejoradas arroz-pasturas para sabana nativa y pasturas degradadas en suelos acidos de América del Sur. *In* E. P. Guimaraes, J. I. Sanz, I. M. Rao, M. C. Amézquita, & E. Amézquita (eds) Sistemas agropastoriles en sabanas tropicales de America Latina. pp 232-244. CIAT, Cali, Colombia & EMBRAPA, Brasilia, Brazil.

SAS/STAT. 1990. SAS/STAT User's Guide. Version 6. Statistical Analysis System Institute Inc., Cary, NC. pp 1686.

Scherr, S. J. & S. Yadav. 1996. Land degradation in the developing world: implications for food, agriculture and the environment to 2020. International Food Policy. Discussion Paper 14. Research Institute-IFPRI Food Agriculture and the Environment IFPRI, Washington, D.C., pp 36.

Soil Survey Staff. 1994. Keys to soil taxonomy. Pocahontas Press, Blacksburg, VA.

Spain, J. M. 1990. Neotropical savannas: prospects for economically and ecologically sustainable crop-livestock production systems. Paper presented at an International Seminar on Manejo de los Recursos Naturales en Ecosistemas Tropicales para Agricultura Sostenible Bogotá, Colombia

Thomas, R. J., M. J. Fisher, M. A. Ayarza, & J. I. Sanz. 1995. The role of forage grasses and legumes in maintaining the productivity of acid soils in Latin America. *In* Adv Soil Sci. Series. Soil management: Experimental basis for sustainability and environmental quality pp 61-83. Lewis Publishers, Boca Raton, USA.

Tiessen, H. & O. Moir. 1993. Characterization of available P by sequential extraction. *In* M. R. Carter (ed) Soil Sampling and Methods of Analysis. pp 75-86. Lewis Publ., Boca Raton FL, USA.

Tiessen, H., I. H. Salcedo, & E. V. S. B. Sampaio. 1992. Nutrient and soil organic matter dynamics under shifting cultivation in semi-arid northeastern Brazil. Agric. Ecosys. Environ. 38: 139-151.

Tiessen, H., J. W. B. Stewart, & C. V. Cole. 1984. Pathways of phosphorus transformation in soils of differing pedogenessis. Soil Sci. Soc. Am. J. 48: 853-858.

van de Geijn, S. C., & J. A. van Veen. 1993. Implications of increased carbon dioxide levels for carbon input and turnover in soils. Vegetatio 104/105: 283-292.

Veldkamp, E. 1993. Soil organic carbon dynamics in pastures established after deforestation in the humid tropics of Costa Rica. Ph.D. dissertation. Wageningen Agricultural University, Wageningen, The Netherlands, pp 117.

Vera, R., R. J. Thomas, L. Sanint, & J. I. Sanz. 1992. Development of sustainable ley-farming systems for the acid-soil savannahs of tropical America. An. Acad. Brazil. Cienc. 64 (suppl. 1): 105-125.

White, R. E. 1997. Principles and practice of soil science. The soil as a natural resource. Blackwell Science, United Kingdom. 3rd Edition. pp 348.

Williams, J. D. H., & T. W. Walker. 1969. Fractionation of phosphate in a matureity sequence of New Zealand basaltic soil proflies. Soil Sci. 107: 22-30.

Submitted to the IIED

Networks of Agricultural Information Dissemination in Emuhaya, Western Kenya

Michael Misiko (TSBF-CIAT), Joshua J. Ramisch (TSBF-CIAT) and Leunita Muruli (University of Nairobi).

Summary: Researchers interested in technology dissemination are increasingly targeting farmer-to-farmer extension techniques. However, farmer networks form for a variety of reasons, and different actors perceive their benefits in many different ways. This paper describes the role of social networks in soil fertility management among small-scale cultivators in Western Kenya. Data for the study were collected from farmers using a semi-structured questionnaire, group discussion, in-depth interviews and direct observation. By and large, agricultural activities still dominate the agenda of rural community institutions. However, the exchange of soil fertility is increasingly accorded low priority in social interactions between farmers, because of poor returns from farming under current conditions of land and labour scarcity. Many farmers put greater priority on using networks for business, formal employment, politics (favours, handouts, appointments, etc.) or infrastructure development. . Networks of farmers are formed on the basis of friendship, proximity and buffering against uncertainty. These factors are effective reminders of the value of networking within community institutions. These findings have important implications for agricultural technology dissemination and adoption in developing countries.

1. Introduction and Objective

The complexity, diversity and peculiarity of rural communities are increasingly being appreciated in research and development work. Social dynamics, like geographical, cultural, soils' physical and biological aspects of a given community pattern agricultural practices. This paper gives a systematic view and analysis of social networks in community institutions and demonstrates their importance and significance in the process of dissemination of agricultural knowledge.

This paper is a result of a study within a BMZ-funded Project of the Tropical Soil Biology and Fertility (TSBF) Programme. The project sought to involve community institutions in the dissemination of agricultural technologies, and therefore studied mechanisms that could be effective in a socially heterogeneous farming community (Emuhaya, Vihiga District, Western Kenya). Some of the important matters brought to light in this study include:

- There were strong social networks among local farmers. Important soil fertility knowledge given to the few farmers who had been involved closely in research and extension filtered to many other farmers through networks.
- However, the content and scope of the knowledge was curbed in the process of dissemination. This resulted from the nature of the existing research links, which currently emphasise vertical rather than effective horizontal sharing of information.
- The wide variety of social problems facing local farmers constrained their search for soil fertility knowledge. Farmers' efforts were diverted to short-term endeavours that ranked as more important.

The understanding gained on networks in community institutions has provided a stage for wider and more meaningful involvement of farmers in research and extension. This paper (i) describes networks among farmers, (ii) demonstrates the importance of networks in community institutions and (iii) explains the function networks play in disseminating agricultural technologies among rural farmers.

2. Recent Perspectives on Networks

> "…[I]t is clear that agriculture today is often individualistic, with farming households increasingly going it alone. But in times of trouble, such as following a drought … and labour is critical to ensure a good harvest, networks are re-established and co-operative behaviour is very evident. Social networks based on lineage relations and friendship thus

may not be critical to agricultural production in all years as they were in the past, but they are certainly of vital importance as a means of offsetting extreme hardship' (Scoones *et al* 1996:35).

Social networks have an important role in the lives of rural communities. In the recent past, research has been done to understand networks and how they function. This knowledge needs to be synthesised, developed and analysed with the view of enhancing dissemination and adoption of agricultural technologies. Lack of understanding or inadequate appreciation of networks will impede dissemination of soil knowledge.

Existing networks can be exploited through engaging community groups (IIRR, 1998). Because group members are themselves typically linked by a variety of network ties, individuals within the group are able to call on collective resources, such as reciprocal labour exchange (Sikana, 1995; Scoones *et al* 1996). Well-functioning groups develop a spirit of "…unselfconscious showing, sharing, and checking… [such] Groups have an overlapping spread of knowledge which covers the wider field and crosschecks" Chambers (1992:41). That implies that farmers of different sorts in such institutions share different types of knowledge and demonstrate or verify it in the process of interaction. By introducing technologies to strong groups comprised of well-networked individuals, researchers may have at their disposal a strong framework and impetus for the adoption of technologies (Sharp and Kone, 1992: 8).Even if strong groups permit the successful diffusion of technologies, researchers and extensionists must be wary of calling immediately for the strengthening (or establishment) of new community institutions. Farmers' institutions have developed and operate within a local context where they may be effective, but farmer groups on their own rarely have influence on higher-level decisions concerning policy. Similarly, because most of the rural population is resource poor, their institutions frequently have weak financial bases. This constant vulnerability does not allow such institutions to bargain with external donors or agencies on equal terms, and leaves them open to having priorities imposed upon them. Since many governmental and non-governmental organisations are eager set up *their own* farmers' organisations and to shape them in line with their ideas and ideologies, it is therefore crucial to establish practical guidelines through a truly inclusive and acceptable arrangement (Pertev and King, 2000). Empowerment should be about organisation, strengthening networking at grassroots structures. Allowing or enabling democratic control of members on these structures will help establish trust and effective vertical relationships.

Although "communities" (or even farmer groups) may have boundaries and memberships that appear discrete and accessible to outsiders, social networks are not confined solely to those units. Rural people participate and invest in a diversity of social networks, whose value lies exactly in their wide thematic scope and geographic coverage (Adamo, 2001). It is ultimately going to be more sociologically and culturally sensitive, as well as more sustainable, to identify the range of local networks that could be used as potential entry points for different research activities (Sikana, 1995).However, it is unrealistic to expect that the interests and priorities of farmers' existing institutions will necessarily correspond with those of researchers. For example, Verma (2001) observed in Western Kenya that soil fertility concerns were not top priority for many farmers, even though land per capita is diminishing and the soil fertility in this region is under serious pressure. Greater worries about disease or marital security in fact constrained many households' efforts to conserve soil fertility. Truly participatory technology design will emphasise farmers choosing research activities relevant to their needs that also build on their knowledge of the farming system and their familiarity with local technologies (Haverkort, 1991).

3. Methodology

The process of study involved both individual actors and collectives in an effort to assess their links and roles, and to outline opportunities of better engaging community institutions for research and extension. To get a comprehensive view of the process of sharing of soil fertility knowledge, this study targeted community institutions, interviewing members of these institutions and focussing on key informants.

Ten community institutions were purposively selected on the basis that (i) they were engaged in agricultural activities, (ii) held regular meetings, (iii) had been in existence for more than one year and (iv) engaged in information dissemination in several ways. Seventy-eight questionnaire respondents were randomly sampled from 334 members of these selected institutions. Seventy-eight (23%) was representative given the nature of the study, physical size and population density of the area. The purpose of the study was to maximise access to qualitative information from a group of respondents knitted in social networks. The researcher therefore deliberately selected a diversity of informants who were most likely to provide articulate answers, explanations, descriptions, proposals, and experiences concerning the complex issues of social networks. Eleven key informants were selected purposively. These informants included people with leadership roles and responsibilities (*Maguru*), those respected in the community, people who had worked in that community and had accumulated essential knowledge and experience in local agricultural aspects, with valuable opinion on community organisations. Some had participated in the project before and had valuable opinion on agricultural research. The researcher carried out several informal interviews, focus group discussion (*FGD*) and group interviews, engaged repeatedly in participatory learning and observed various phenomena to verify or identify data.

The study (and therefore this paper) was largely based on qualitative data: on open conversations[1], in-depth and group interviews, comparisons more than counting, informal *FGD* and brainstorming, stories, exchanges and consensus where necessary. Analysis was therefore largely on the spot, while the study occurred.

3.1 – Study Area – Social. The study was conducted in Ebusiloli sub-location of Emuhaya Division in Vihiga District. The Luyia speaking people called **Abanyore** inhabit Emuhaya. They formed a close community in which there was much sharing of life between families and neighbours (Osogo, 1965). Today, a strong individualism is replacing this community consciousness. Since independence, their social system has noticeably transformed and the predominant religion is Christianity (Muruli *et al*, 1999).

In 1995, Vihiga District had 948 registered women groups with membership of 28,440. There were 557 self-help groups (no membership given) and 168 youth groups with registered membership of 4,543 (Republic of Kenya, 1997). Information acquired from the divisional headquarters of Emuhaya during the study show that there were seven registered groups in Ebusiloli (Courtesy: Ministry of Social Services, Emuhaya Division). According to Muruli *et al* (1999), more than sixty three per cent of farmers in the area actively participate in different kinds of registered and unregistered community institutions.

3.2 – Study Area – Physical. Emuhaya has loamy sands that support the growing of maize, sweet potatoes, coffee, beans, finger millet, sorghum, sugar cane, and horticultural crops (Republic of Kenya, 1997). However, these soils are quickly losing their fertility through leaching and over-cultivation due to limited land sizes per household coupled with low usage of suitable farming innovations. Vihiga district has an annual population growth rate of three per cent. Emuhaya's population density is about 1197 people km^{-2} (Republic of Kenya, 1997).

4. Social Networks: Is There Room for Soil Fertility Knowledge?

Although networks are the implicit cornerstones of the farmer-to-farmer strategy for disseminating soil knowledge being preferred in many projects, many academic analyses of social networks create a romantic picture that may not be regarded as very useful by agricultural workers. Such texts may for example display a harmonious existence and functioning of networks in community institutions. Such information may not outline specific areas that can be exploited to enhance dissemination of agricultural knowledge. Of course, forming social networks is not an end in itself. The communication of information and reciprocity of networks are in reality a survival mechanism for many poor farmers. They provide the means to acquire material and non-material benefits.

Results from the *FGD*, the study survey and in-depth interviews show that networks play a

[1] The researcher recognized the essence of getting farmers' message clearly and as accurately as possible. Before any *FGD*, interview or meeting he met with some participants to train them in note taking so that he would concentrate on keeping conversations flowing. However, the researcher wrote down brief notes on important issues in a small notebook. Key vernacular terms were written. Maintaining conversation flow in discussions is vital if one hopes to keep participants *interested* in the study.

dominant role in agricultural production. The question remains, however, whether room exists for soil fertility knowledge in these social networks? Soil fertility knowledge may be spread or utilised depending on the type and strength of networks in operation. The following expressions by two farmers attest to this.
Boaz:

> "… [S]ome people are just friends. They do not share a lot and that is why they do not work closely. But me, I value my friends and neighbours very much. We exchange items like the 'black beans' (*KK15)* and soil knowledge from the research people and contribute a lot to our farmers' research group. The group and also my youth group are very beneficial. I also participate in *barazas* of *Maguru* [village headmen]. They [*Maguru*] are [also] useful because they help us to deal with thieves…."

Alexander:

> "Our group is made up of people with similar interests who know one another well. When there is a demonstration here [researchers have a trial plot on their family farm], all members attend and learn something. We have been planning to try some of those technologies [leguminous cover crops such as *Desmodium*] on our group's plot but we do not have enough farm and money and prefer to plant *Napier* grass for sale. …[B]ut we cannot convince others who are not in our group to do what we do not do. They will say, 'If it is good why have you not tried it?' So that is hard, when they see the things [improved fallows] on the trial plot they say, 'You [the family] have been given money for this research and we have not."

These verbatim accounts show that soil fertility knowledge is likely to spread faster among farmers bonded by strong networks, who will share valued information amongst themselves. However, as the second farmer implies, even information that is known to be potentially useful will not spread without it also being *seen* to be beneficial. In this case, because the soil fertility practices being researched were not perceived to offer immediate financial gain, farmers of that group were not keen to try them. This reluctance within the group of research farmers effectively blocked the further sharing of useful soil fertility practices, even though the research farmers might have been part of extensive and strong networks.

This suggests that farmers would more likely engage in social talk about something immediately tangible, like a good yielding crop variety, than they would about something more abstract or complicated, such as a management practice that would directly support that crop by improving soil fertility. It is easier to talk about the benefits of a technology than it is to explain exactly how those benefits were obtained. Nevertheless, most of these new technologies rely on sound management. Because farmers will master this management at differing rates, many may not feel confident enough to discuss soil fertility management, especially the new practices that research is still yielding. Unfamiliar technologies (such as planting of *Desmodium* sp.) will therefore not enter easily into local discourse and practice. However, *Crotalaria ochroleuca*, another of the improved fallow species being researched and disseminated is well known by farmers because it is locally eaten as a vegetable. However, if it is known and liked then not enough quantities may be left in the farm to mature so as to contribute to soil fertility. Farmers may generally view it and discuss it as food, not a soil fertility management plant. Therefore knowledge about it may not necessarily be inclined toward improvement of soil fertility.

One benefit of strong social networks is the provision of social fora to express or explore new ideas. While most farmers did not necessarily have access to such venues, two examples show how strong networks did allow valuable soil fertility information to be exchanged between members and sometimes used on collective plots. For instance, the 19 members of Emanyonyi Women Group spent between ten and sixteen hours (11-20%) of their working daytime in a week together. Discussion of soil fertility was part of their deliberations on the agricultural and forestry projects that generated their collective income. Each and every member was an *official* in some capacity. Because this group had several ventures, all the members had to actively contribute labour, cash and importantly information or logistics. Their stronger networks had not just inculcated discussion of soil fertility information; they attracted outside support (especially training and exchange visits). Similarly, Escrava Youth Group whose members were young (18-35), perceived soil fertility research as an opening to enhance returns from their farm projects. During a visit to their plot, the researcher noticed that they had embraced some of the biomass transfer practices that were under research. Most members of this group did not own individual plots, yet their willingness and ability to share soil fertility knowledge was astounding. Only two of the 17 members were participating in TSBF trials, but the level of awareness among the rest was significant due to their attitudes. Networks as strong as those found within these two groups act as invaluable 'talking spaces' and provide counsel to members. It is important for locals to be able to present and discuss new ideas especially in their own language and setting. This may present one way of understanding how farmers conceptualise and use new soil fertility ideas.

Farmers with strong networks were able to exchange valuable knowledge on soil fertility (i.e.: *biomass* transfer and fallow cropping practices) and take certain collective investment risks. In such cases, the general 'farming' talk also led to tangible exchanges such as seed, agricultural labour, cash, manure, land use and other resources. Unlike average networks, strong networks allowed for a relaxed form of balanced *reciprocity* where one did not necessarily have to 'reply' immediately or directly. For example, one would volunteer one's farm for collective farming without expectation of direct payment from members. One was clearly aware that some members did not have sizeable farm to allow for collective activities.

5. The Essence of Networks

In spite of the decline in soil fertility and the ensuing low farm yields, farming remains a treasured activity, even if it is not one that receives adequate national support. Most people in the study area practised at least some form of farming regardless of their main occupation. One adaptive research farmer, Nashon, portrays this in the following explanation:

> "I discuss many things with people. I sit in the [farmers research] group, and I know most of us want to spend a lot of energy on small businesses or to look for office work [i.e.: formal employment]. As you have known, our farms are very small and we are very interested in growing [i.e.: getting money] because we are very poor. This work you are doing will help us also, to train our people in agriculture, to teach us soil fertility practices so that we can increase our maize harvest. Let me tell you something, we feel very fastened to farming even though our maize [harvest] is pitiable. Yet one's own harvest is very precious. If your children want to roast [maize], they will not steal from your neighbour's farm [if your farm has any maize on it?]. So you see, soil fertility is important because if you fail to plant, or do not harvest anything, your child may become a thief and people will say you are lazy. So for me, I ask for soil fertility information from you the agriculture people [researchers and extension agents] and my friends [locals] to help us…."

As this commentary shows, farmers engage in agriculture not because it is inherently profitable but because it is an essential part of life. In this respect, it is wrong to conceive of peasant cultivation as a 'technical industry' *per se*, since it is also clearly a socially-based activity. Informal discourse within farmers' networks is commonly about what are accepted norms. Resources were 'injected into the soil' even when returns were small, in part because someone who 'failed' to demonstrate capacity as a 'farmer' would risk criticism as 'lazy', a 'thief', etc. Clearly the discussion of new soil fertility practices would fall within such local 'normal' discourse, but quantifying these discussions would be difficult.

Nashon is however uses his local networks only cautiously, since he preferred not to rely on locals for important information. He stated that there are certain hindrances to the flow of useful knowledge within his experience of networks, especially related to the sharing of gossip (*etsimbemba*):

> "You hear 'So and so said this or that': how do you rely on that? *Avanti vayansa okhuchaya* (others will despise you), instead of learning something from you. *Valala vali nende omwoyo kwe imbotokha nende wivu* (others have bad feelings and are jealous), others are false pretenders (*vachuaji*), they pretend they know it all and few are delinquent (*avahalifu*)."

Such feelings were particularly common among men. Many farmers cited such explanations as obstacles to the establishment of stronger networks with certain people in some community institutions. Farmers would rather keep away from those they regarded as pernicious, even if it meant foregoing access to useful information. An implication of this wariness is that in selecting resource people researchers need to be keen to avoid putting locals regarded as 'unpleasant' on the frontline. If they have bad reputation, the project will not have a good standing and locals may not feel enthusiastic about the research.

On the other hand, some issues were perceived as so fundamental that farmers were encouraged to unite and create stronger networks. The main reasons behind strong networks of interaction in community institutions gathered in the sample survey have been given in Table 1 below.

Table 1: Percent Distribution of Reasons for Participation in Community Institutions

Exchange/Benefit	Responses	Percent of Responses
Improve livelihood	49	28.5%
Cash – credit, assistance, savings	36	20.9%
Agricultural development	35	20.3%
Assistance – in distress	27	15.7%
Advice and information (general)	15	8.7%
Administrative issues, *Maguru*	6	3.5%
Links to donor and agricultural organisations	3	1.7%
Employment, to earn some money	1	.6%

The most commonly mentioned motive for participation in community institutions was to improve members' livelihoods. Table 1 also reveals that at the grassroots, agriculture is an integral part of the broader system of economic and social contexts that shape involvement in social networking. . *FGD*, group discussion and informal interviews showed that earnings from other occupations such as formal employment and business are used to improve soil fertility. For instance, poor performance in business or a delay in salary payment affected purchase of fertiliser or seed. Therefore, networks formed on non-agricultural exchanges directly or indirectly support agricultural production. It therefore implies that narrow observation and dealing with local institutional networks as if they were purely 'agricultural' in orientation can be misleading.

6. Networks in Community Institutions

The history of an institution's development, and the nature of its members' networks significantly influenced the sharing of valuable knowledge, collective action and attitudes and behaviour. The main reason behind the existence of strong networks was the need to improve livelihood foundations. The strength of these networks depended on actors' trust in each other. If this trust was significant, they would invest their time and money together in group activities, one consequence of which would be the sharing of soil fertility knowledge.

Nevertheless, the process of inception of the various institutions that existed was not unilinear. The strongest community institutions resulted from one or two individuals inviting their close friends who shared similar problems and aspirations. Leadership in such situation was achieved through mutual agreement, willingness and suitability. Duties would be delegated to any chosen member and everyone's input in drawing a constitution was valued. Constitutions were precise, mutual agreements, normally as written documents, but a few were verbal. They outlined the objectives, procedures and conduct of members in an institution.

Researchers facilitated the creation of one farmers' research group, while other institutions were mobilised by local resource persons, church leaders, opinion leaders or even politicians. All the institutions that were selected for study had been in existence for over two years. The oldest was a labour group that had been in existence for over 25 years. Institutions that were formed and defined by narrow schemes such as to gain access to campaign money shortly before the 1997 presidential funds drives did not last long. They were mobilised by politicians and packed by people who did not have strong networks. Soon after inception, jostling for leadership and access to funds ruined them.

There were several factors that were favourable for the existence of an institution. The overriding factors included the desire and dedication of actors in networks. Actors relied on existing traditions, and social and cultural attitudes conducive to co-operative participation and common social action. One discussant (Gerishon[2]) reflects this in the following remark:

> "Our people have always had reasons to co-operate. Since the time of my great-great-grandparents, Abanyore have assisted each other in wars, famine, building huts, farming, hunting, raising children and so on. Many of those things are done individually now while others no longer matter. But, you never know. You may fall sick or even die tomorrow…. I have to maintain some relationship with some people, in the event that I need help they should be willing and available to assist me."

The success of strong groups also tended to be self-reinforcing since, when members' financial stake in their group was significant they tended to participate actively in an effort to ensure that the group operated efficiently.

The strength and nature of interactions within local institutions was significantly shaped by proximity. Most residents had been living in the study area among their lineage relatives for many generations. As a result, local level networks were considered strong. For example, members of Alexander's youth group live nearby and formed a very active institution. However, like other groups, the quality of networks was determined by friendship based on age and socio-economic factors.

Table 2 shows that friendship was very important for determining group membership, especially within women and youth groups. Women groups, followed by youth groups, were identified as having the strongest network ties. These two drew membership from across the study area and beyond. Women were more available than men for meetings, able to work with young members, and had fewer leadership wrangles or funds mismanagement problems. Theoretically, networks were vast and primarily open. For instance it was not possible to map out all networks of a member of a community institution. But the nature of networks and goals of an individual defined the level of freedom to move in and/or out of an institution. For instance, a man of sixty-eight years was unlikely to share or discuss goals and aspirations with his twenty-year-old daughter in law. Other than age, this would also be culturally abhorrent.

Table 2: Composition of Community Institutions

Type of Institutions	Close Friends	General Friends	Close Relatives	Clan Members
Women Groups	31	8	3	6
Youth Groups	21	10	2	16
Farmers RG and Self-help Groups combined	11	10	2	16
Totals	63	28	7	38

Many of the respondents belonged to more than one institution. However, this did not necessarily reward them with soil fertility knowledge. Members almost always affiliated closely with cliques of their closest friends. In fact, there was evidence of lack of practise and even awareness of notable activities done in other institutions in spite of the fact that some members belonged to both institutions. For instance, one institution had very strong networks that were evident from frequent weekly meetings, loyal contribution of subscriptions, high attendance in meetings, participation in collective activities and sharing of important farming and other knowledge. Members of this group had been trained in tree planting, improvement of soil fertility through improved fallow systems and biomass transfer, basketry and so on. Some of these skills and knowledge had not spread to neighbouring institutions to which some of the members belonged. It is possible that the content of the information that had percolated was very ordinary. It would take a longer period (more than one year) for a remarkable amount of soil knowledge to pass to other institutions and for them to use it.

[2] Gerishom (62) worked with the Railways corporation in Uganda and Kenya before his retirement. He is a committee member of a water project in his village and his wife is a key member in one of the most active women groups in Ebusiloli. He is very knowledgeable about the social history of his people, and his ability to critique, use proverbs, analogies and comparisons from afar was impressive. He has a zero gazing unit and part of his farm-plot is used for TSBF trials (BMZ Project). Unlike other verbatim, his has been directly written in grammatical English because it was entirely recorded in English.

One explanation for the low exchange of ideas was that the new practices were not seen to promise good enough economic returns to compete with other group investment opportunities. Local farmers noted that agriculture is very difficult to capitalise. For example, farmers have trouble obtaining credit for new farm ventures because the profits to the lender are not assured. Furthermore, it was not feasible for most households or groups to engage *only* in agricultural activities, since land pressure is intense and it was difficult to acquire sizeable farms (over one acre). Even if farmers planted cash crops like kale or other vegetables, the amount they would fetch was little. Such collective proceeds would be meagre when subdivided among members of a given institution. Therefore, networks were not used exclusively for agricultural work. For example, if members set one day a week to work on their group plot, they would spend the rest of the week on other enterprises like selling maize or firewood beside the road. The desire for cash (specifically capital) was important in this respect. There was a resolve to engage in small businesses within homesteads or at local market centres and many groups intended to purchase plots, to construct shops, rental rooms, eating rooms, and so on. Such ventures were seen to be more profitable uses of local 'farm' plots than using that land for agriculture.

Smaller institutions of about fifteen were more organised and committed to their course. It is however not possible to map out the boundaries of networks and thus determine an ideal size of farmers' institution. This study points out that it is preferable to work with institutions shaped out of a 'natural' process rather than try to create networks on the basis of research needs. If the goals of research cannot fit somewhere within the wider objectives and aspirations of local farmers, then there is arguably no business to be done with those farmers.

In circumstances where local institutions are not already strong, creating or strengthening those existing networks can be worthwhile. It is not uncommon to find farmers who live nearby, share common agricultural problems and have strong networks, but who are yet to form an organised institution. In other words, the formation of a group does not happen spontaneously, it often takes the initiative of a local opinion leader or someone else to facilitate.

7. The Strength of Networks

According to Ritzer (1992), the strength of networks is directly dependent on the returns accruing from them. In reality, farmers do not mechanically act in social networks while making cost-benefit analyses. For instance, most farmers understand that seeking and maintaining links with researchers and extension workers can assist them to improve their soil management practices, among other benefits. Yet even where the researcher-farmer relationship is strong, it does not follow that information shared between them will spread to other farmers. The nature of farmer-to-farmer interactions is a function of local social relations, as explained by this fifty-six year old *Liguru (*village leader) Bernard:

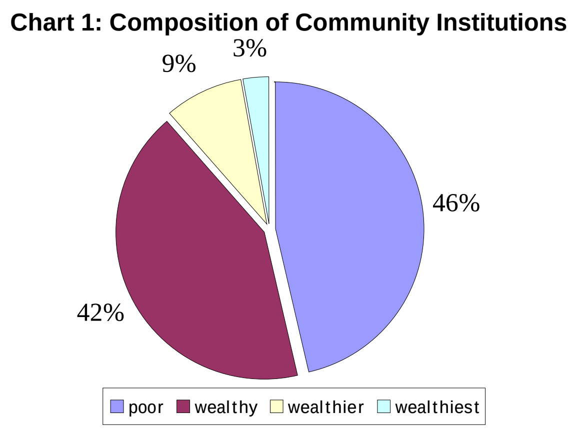
> "Many farmers in your projects do not want others to know what they are doing or how they are benefiting. They feel privileged and under no obligation to spread the knowledge they are given. They wish to stay on top by being advantaged in such ways…. Not all are like that, but it is hard to know. You [researchers] should do things openly. You should involve many people. Let us see, who has joined us here since you came? They [farmers] think it is a private deal between you and me. Those who come may not want soil fertility information but to know our affairs".

The acute under-utilisation of existing technologies is often construed as 'conservatism' or 'traditionalism' on the part of rural farmers. However, as Bernard's comments show, new ideas are not like seeds that can be sown on neutral ground. Instead, they are always being planted in environments where the "safeguarding of vested interests and a *way of life* is very conscious"(Mbithi, 1974: 60).

Networks are dynamic. Regardless of the rules and codes of conduct within community institutions, the networks between members are never constant. The more committed members are to their institution the stronger their networks. The more they exchange information and achieve their goals, the higher the chance that they will remain in those institutions for long.

Congenial discourse within an institution creates an air conducive for association, but people will enter and leave institutions as they choose. Fortunes of members keep changing with new experiences, beliefs, opportunities, and even assumptions. In the face of such potential fluidity, an institution's organisation is important. Within institutions that had strong networks, members had unambiguous but to all intents and purposes transcending roles. In institutions where the role of each member was noteworthy, members had a feeling of value and merit. Such groups could endure without significant turnover of membership. However, most institutions did not function like this: rather, they had a small, core membership that provided continuity and direction. Most of these institutions were made of economically poor farmers. Such groups would not persist without the constant initiative of relatively stable members to invite, mobilise and encourage others to join or even remain in those institutions.

Informal interviews, in-depth interviews and discussions showed that relatively richer farmers were seen as sources of casual employment, money handouts, food, tools, and so forth. Contribution of resources to institutions was supposed to be uniform for all members in given institutions. Nevertheless, relatively prosperous members of community institutions were expected to be 'monetary pillars' in times of difficulty. Chart 1 below shows the distribution of members of institutions in various social classes as perceived by farmers. These data were gathered in wealth ranking exercises that were carried out during the study.   While poorer farmers acknowledged that there were also members who were knowledgeable in soil conservation, their value to the group as 'knowledge reservoirs' was rarely acknowledged or explicitly valued. The low flow of valuable knowledge from resource persons was also made notable as a result of their small number.



Discussion also revealed that women were more likely than men to share resources in institutions. While soil fertility found its way (explicitly) on to the agenda of their discussions on relatively few occasions, women's strong networks were however built upon the understanding that they were more vulnerable to hunger and other local problems than men. It therefore became necessary for them to discuss crop performance. Furthermore, women's position in the homestead was precarious, as their stability depended considerably on their husbands' decisions. If they transferred savings to their homesteads, those savings would be counted as their husbands'. It was therefore rational to keep some of their savings with the group so as to safeguard it. Consequently, regardless of how women were perceived (wealthy or poor), their involvement in community institutions was beneficial. For instance, women perceived as relatively well off had children in schools and their parcels of farmland were relatively larger. If their husbands declined to hire labour, they were made to turn to their institutions for labour. In worse circumstances, poor women received comfort from these institutions. They would for example withdraw their investment in the event that they were divorced[3] to 'look for life' elsewhere. The proceeds of institutions were not necessarily immediate or for immediate use. As Kanogo and Maxon (1992), (in Nangendo, 1994:353)

[3] Abanyore are patriachal and patrilocal. When a woman is divorced or 'flees away', she is therefore expected to live elsewhere. Normally, young women would return to their parents or remarry. But those over forty-five would find it hard to settle back in their parental homes or to remarry. They would turn to their savings in groups to start business or resort to other dealings.

say, members of these groups:

> "pooled labour resources and shared the proceeds of that labour, and this produced a spirit of sharing and unity. People joined these groups even if they did not immediately need the services provided."

Hartwig (2000:34) observed in a similar vein that:

> "The groups are open to precisely those women who … progressing from dealing with specific problems in the women's work and life, provides the stimulus to exchange information and develop their education."

8. Reaching the Wider Community

To a casual observer, the networks in local institutions are besieged by competition just as much as co-operation. It was however found that competition in these institutions acts as a reminder that farmers do not always network because they are homogenous, but rather because they want to fight poverty. This finding is reflected in this revelation of a sixty-year-old key informant (Repha):

> "Members of my group have different behaviour but have similar ambitions. We therefore share agricultural information. All the people you see sitting together in community institutions recognise that they cannot succeed by sitting on others (undermining others). … [Y]ou give some people around here information, they refuse to use and instead visit me at night[i.e.: steal her crops]. Such are the people who want money from researchers, though they need information urgently. If you get even five people who are serious, work with them. Do not follow masses, your success will be small. Work with few groups and if others *see results*, they will move closer, like now, many of them want to know about the black beans (*KK15*). …[I]t is not that they are not involved, they do not involve themselves. I always invite them to my farm whenever visitors (researchers) come. Few come, some do not, yet they all want to *see results*."

Her emphasis on tangible results reinforces that that research must be seen (and known) to benefit especially poor farmers. If the agricultural technologies that research is generating can be shown to be useful and sustainable, then researchers may rely on networks to reach the wider community. During the study period, it was found that farmers were willing to participate in collective research activities if research would directly benefit them especially in the short term. Some of the cover crops (especially *Desmodium,* planted with *Napier* grass etc.) were appreciated. Some farmers liked this particular leguminous cover crop because it would increase the harvest of *Napier* grass, which is an important cash crop to many institutions that were studied. However farmers were disheartened due to unavailability of seed. Moreover, if these legumes could be consumed (like *Crotalaria*) it would be pointless to vigorously disseminate knowledge on their usefulness. Such knowledge would spread quickly through social networks and farmers would first adopt them as food crops regardless of what scientists told them.

Table 3: Farmers' Identified Sources of Agricultural Information in Western Kenya

Information Source	Information Frequency	Information Source	Information Frequency
Ministry of Agriculture (government extension service)	649	Research institutions	148
Schools	396	Stockists	94
Other government bodies	329	Informal networks	1523

The importance of informal ways of information dissemination and sharing are difficult to overstate. Table 4 below shows results from a survey carried out by TSBF in 1998, which included the study area. Informal networks were mentioned more than twice as often as being a source of agricultural information than the government extension service (the next most cited source).

Despite its prevalence, the success of research and dissemination using informal channels is not straightforward. For instance, knowledge transmission is not based on simple communication channels, conduits or linkages, it involves human agency and occurs within socially and politically constituted networks of different actors, organisations and institutions. Thus, communication occurs through the discontinuous, diffuse, value-bound interactions of different actors and networks (IIRR, 1998; Scoones and Thompson, 1993). At the same time, researchers should not expect that the content of 'their' information would pass through networks unaltered. For information to be locally relevant, it must be continuously tested and validated. Researchers relying on local networks for knowledge diffusion must also embrace the idea that the learning process involved will be 'two-way', with lessons to be learned by both farmers and researchers.

Because networks depend on the decisions of individual actors, distribution and content of knowledge cannot be precisely monitored. Network channels filter information differently to different actors. Effective dissemination of information will therefore have to rely on involving collectives. Relying on stronger networks in community institutions represents best the promise of wider reach to poor farmers. Giving information to as many farmers as possible at once improves the chances of information spreading widely through existing social networks (Grigg, 1995).

9. Participation Facilitates Learning

Farmer-to-farmer extension that involves community institutions provides a variety of both formal and informal settings for farmers to learn and share knowledge through participation. Researchers have been working with community institutions in the study area in a variety of activities. The most important venues cited by respondents included: demonstrations mentioned forty-three times (55.1%), field days mentioned thirty-seven times (47.4%), farm visits mentioned thirty-six times (46.1%) and training workshops mentioned twenty-two times (28.2%). These activities presented convenient avenues for researchers to interact with farmers while farmers also got to learn from each other. Although farmers lived close by to one another, in normal, daily interactions they reported rarely finding such valuable occasions or venues to learn new ideas (or even unlearn poor practices). Although researchers considered such 'on-farm' work to be less formal than their other types of interactions, farmers strongly associated such fora with technical knowledge. The talk by both farmers and technical staff was not general; it was direct and vital in enabling farmers to separate facts and reality from rumours. Farmers got to learn with confidence – information validated as 'science'- and to assess things through their own eyes. Such fora also encouraged change, unlike informal interaction where conformity with the status quo was often the norm.

Despite the high status afforded to the formal activities, all seventy-eight farmers reported sharing the bulk of their information through informal activities. Such activities included group meetings, interaction at local market centres, farmer-to-farmer visits, singing and so on. For instance, when outside 'visitors' came to the village, women would sing songs containing soil fertility messages. While this certainly served to entertain, it was also a very powerful means of disseminating soil fertility knowledge. One may conclude that those songs bear witness that women had taken into account the soil fertility practices that research was yielding. The songs also further strengthen networks among members and encouraged visitation.

During formal events such as demonstrations, consultations between farmers and specialists in a less formal, impromptu atmosphere before dispersing helps answer questions that could not have been addressed during the formal programme of the occasion. This presents an ideal arena for farmers, especially those who would not normally speak in public gatherings (such as poorer women and children) to appropriately learn.

Researchers need to take explicit steps have to respect women by listening to their side. Otherwise women's often-placid approach may sometimes be mistaken for ignorance or disinterest. Because resource poor farmers (especially women) are besieged by numerous problems, scientists and extension agents should expect them to bring up topics that are not directly connected with soil fertility. Being the topic of the day, soil fertility may only act as an 'entry point' for dealing with broader development issues. In the midst of what appeared to be a soil-focused discussion, a participant may, for example, ask for a water or dairy project. Such concerns are common and, while seemingly 'off-topic', the outsiders' remarks on them will be keenly noted. Farmers may afterward reflect on what they *did not hear* from the researcher, and it is important to bear in mind that such dialogue is not uniquely a 'research' endeavour, but part of a longer-term social relationship. It is neither realistic, nor practical to assume that a topic like soil fertility will feature in every social encounter, as demonstrated by this comment by a farmer (Jairo):

> "I cannot introduce a technical subject like use of fertiliser on the market or while taking *busaa* [a local beer] with my friends. They are supposed to be here listening [referring to a field day]. Furthermore they are not children to be taught on the proper practice anywhere…. However, you [researchers] should keep up, I have observed an increase in the number of attendance by farmers. Also, your activities have encouraged more [community] discussion on agriculture and trees [agroforestry]."

While it is entirely legitimate to focus on soil fertility research, crusading to keep farmers consistent may push them away or simply turn them into 'followers'. For instance, at the outset of this study the researcher explained to farmers that he had gone to the community 'to learn'. However, from rapport development up until the end of the work, farmers expected him to be an instructor. During formal interviews, respondents would keep 'other' issues to themselves. But when interacting informally, they would for example say, "Ooh, it is good you are with us. We look forward to your help…" or, "Take these vegetables, you are a good young person, you can make a wonderful son-in-law…." Farmers who were able to express their various 'off-topic' feelings or remarks and questions were then more willing than before to discuss soil fertility issues. The researcher had penetrated their networks somewhat by allowing the informal 'talk' to be his 'entry point'.

There is also a need to understand that different farmers learn well in different settings. Understanding the learning styles of the farmers who researchers and development agents deal with can assist them to establish suitable platforms and processes. Chart 1 (above) showed that more than three quarters of local farmers were resource poor. The interview process found that most of them preferred a balance between the informal forms of knowledge dissemination that were typical within their groups and more formal means. The following is an example of informal aspects as suggested by a farmer during an *FGD*:

> "…. Those [farmers] who are using your ideas [soil fertility practices] can be selected as examples to show the way. Also, all participating farmers should be awarded certificates. Certificates will remind us about your work and encourage us to talk about it openly."

Such encouragements, while perhaps seeming trivial to an outsider, would actually be like 'adding value' to any information that is provided. Locally, education is highly regarded and any proof that one is knowledgeable may enhance one's confidence. This may not directly contribute to a change in farming practices, but if it can generate enthusiasm in research activities so can it improve communication in social networks.

10. Conclusion and Way Forward

While every farmer involved in this study was involved in social networks, the use of these networks for farmer-to-farmer extension is as complicated as the networks themselves. To disseminate agricultural knowledge through channels that have evolved for a multitude of social, cultural, and economic reasons, one needs to understand the local institutions, agricultural practices and preferences of local farmers. Therefore, researchers and extension workers need to understand the social interactions within local institutions and how these institutions can better serve memberships from varying socio-economic backgrounds.

There is also a need to involve farmers in community institutions directly in the dissemination of knowledge. Transferring more of the research and dissemination process off-station and into farmers' hands should not just be viewed as a cost-saving measure, but one of legitimate empowerment. Currently, local innovation is being hampered by the farmers' (often-justified) anticipation that the researched soil fertility technologies generate poor returns. If farmers can monitor and evaluate their activities, the costs and benefits of innovations can be better understood and a subsequent generation of more relevant and effective technologies will result. We can also expect to see greater farmer commitment and thus the greater involvement of their social networks. Such an evolution may involve unlearning old practices on the part of both development agents and farmers. It was observed in this study, as in previous ones, that greater facilitation and involvement of farmers as full partners in research and dissemination would enhance innovation of indigenous technologies. Researchers and extension agents also need to acknowledge that the *sharing* of information through networks is by definition a 'two-way' learning process, which ultimately generates important understanding of local realities. Questions that need to be clearly understood include: how and when do farmers innovate, who amongst them is foremost in innovating and how do they trust technologies from within and outside and share them amongst themselves?

References:

Adamo, A.K. 2001. Participatory agricultural research processes in Eastern and Central Ethiopia: Using farmers' social networks as entry points. CIAT Network on Bean Research in Africa, Occasional Publications Series, No. 33. CIAT, Kampala, Uganda.

Chambers, R. 1992. Rural Appraisal: Rapid, Relaxed and Participatory. Institute of Development Studies Discussion Paper 311. Brighton: Institute of Development Studies (IDS).

Grigg, D. 1995. An Introduction to Agricultural Geography. London: Routledge. 2nd Edition.

IIRR, 1998. Sustainable Agriculture Extension Manual: For Eastern and Southern Africa. Nairobi: International Institute of Rural Reconstruction ((IIRR).

Mbithi, P.M. 1974. Rural Sociology and Rural Development: Its Applications in Kenya. Nairobi: Kenya Literature Bureau (KLB).

Muruli L.A., D.M. London., M. Misiko., K Okusi., P.M Sikana and C.A Palm. 1999. Strengthening Research and Development Linkages for Soil Fertility: Path Ways of Agricultural Information Dissemination. A Project Report To IDRC. Nairobi: Tropical Soil Biology and Fertility Programme.

Nangendo, S. M. Daughters of the Clay, Women of the Farm: Women Agricultural Development, And Ceramic Production in Bungoma District, Western Province, Kenya. A Ph.D. Thesis. January 1994 Pennsylvania Bryn Mawr College.

Pertev, R and King D. The Essential Role of Farmers Organisations in Developing Countries. In, Wilcke, A (Editor). 2000. Agriculture +Rural Development. Volume 7, No. 1 April 2000. ISSN 0343-6462. Frankfurt: Technical Centre for Agricultural and Rural Co-operation (CTA).

Hartwig, E. Women's Organisations and Self-help Groups: a Step Towards Independence. In, Wilcke, A (Editor). 2000. Agriculture +Rural Development. Volume 7, No. 1 April 2000. ISSN 0343-6462. Frankfurt: Technical Centre for Agricultural and Rural Co-operation (CTA).

Osogo, J. 1965. A History of the Abaluyia. Nairobi: Oxford University Press.

Republic of Kenya, 1997.Vihiga District Development Plan 1997-2001. Nairobi: Government Printer.

Ritzer, G. 1992. Sociological Theory. New York: MacGraw-Hill. 3rd Edition.

Scoones, I. and J. Thompson 1993. Challenging the Populist Perspective: Rural People's Knowledge, Agricultural Research and Extension Practice. Sussex: University of Sussex (Institute of Development Studies).

Scoones, I., C. Chibudu., S. Chikura., P. Jeranyama., D. Machaka., W. Mchanja., B. Mavedzenge., B. Mombeshora., M. Mudara., C. Mudziwo., F. Murimbarimba and P. Zirereza., 1995. Hazards and Opportunities – Farming Livelihoods in Dryland Africa: Lessons from Zimbabwe. London: Zed Books Ltd.

Sharp, R. and M. Kone. African Recovery Briefing Paper No. 5. June 1992. New York: United Nations (UN).

Sikana, P. 1995. The Participatory Training Consultancy on the Assessment and Identification of Formal and Customary Village Institutions. Ministry of Agriculture, Naliandele Agricultural Research Institute ODA Cashew Research Project. Mtwara: Govt. of Tanzania.

Verma, R.P, 2001. Gender, Land and Livelihoods in East Africa: Through Farmers Eyes. Ottawa: International Development Research Centre (IDRC).

Draft

Decision Support Systems for Integrated Soil Fertility Management

J.J. Ramisch and M. Misiko
TSBF-CIAT, PO Box 30677, Nairobi, Kenya

Rationale: Adaptation by farmers of research-designed technologies is crucial for increasing the relevance and therefore adoption of technologies. Adaptive research has to be linked to increasing the capacity of service providers and farmers to disseminate this new information and to ensure effective information flow between research and extension.

Since May of 2002, four interactive participatory events have occurred at a TSBF-farmer demonstration plot in Emuhaya, W. Kenya. Efforts have been made to describe and explain to a wider audience (local farmers) TSBF's process of soil fertility research in W. Kenya. Key among the explanations were that TSBF in conjunction with local farmers and other research institutions have identified soil infertility and related problems as major and are researching on alternative or/and potential solutions.

Some of the technologies that have been researched are being illustrated on the demonstration plot in Emuhaya. These activities include i) improved fallows ii) efficient recycling of residues iii) use of inorganic and organic fertilisers iv) traditional practices like natural fallows and use of indigenous plants among other technologies. On July 31, 2002 farmers and researchers held an evaluative field day and discussions at the demonstration site. Farmers expressed the main areas of strength and pointed out improvements that were needed. On August 16, 2002, farmers and TSBF staff harvested maize on the demonstration plot in Emuhaya. On August 22, 2002 a community discussion was held involving different types of farmers and TSBF staff to assess achievements, limitations and lessons achieved from the activity. On the former day, a pre-harvest evaluation was done, and also ranking of the different plots under different treatments. On the later day, in-depth deliberations were held about the plot and way forward. This was a furtherance of preliminary discussions that had been held during different stages of the demonstration.

The technologies that were demonstrated on the plot include i) efficient recycling of crop residues ii) use of inorganic and organic fertilisers and their iii) different combinations iv) biomass transfer and use of legume trees. Also tackled, and not demonstrated, include use of indigenous plants as manures.

Findings: There was a step-wise pre-harvest review of plots under different treatments by farmers and TSBF staff. Many of the attendants had visited the plot before and many had participated in various or different activities at the site and were already acquainted with the plots. A summary of all activities that had been done on and at the demonstration plot was given and the plots were briefly described; the different treatments included:

	Low quality (maize stover) ↓	Intermediate quality (FYM) ↓	High quality + polyphenols (*Calliandra calothyrsus*) ↓	High quality (*Tithonia diversifolia*) ↓	Control plot (no organic) ↓
No N or P →					
+ Urea only →					
+ Urea, +TSP→					

A rapid pre-harvest assessment of plots was held; first, amongst the first five (with organic inputs only); second, between plots with organic inputs alone and those with different inorganic fertilisers added; and three, amongst those with inorganic fertilisers. This was done to illustrate nutrient contributions of selected inputs.

All maize plants on every plot were counted. After getting the sum of maize on every subdivision, farmers systematically harvested the crop, starting with the control and weighing both stover and maize. Various observations were made, and notes on the following taken by farmers: Differences in dryness, weight, appearance; Effect of striga, other weeds and pests.

Most maize had been twisted, lying on the ground due to a past storm. Low harvest was also blamed on late planting and a long dry spell in June. Farmers said that under normal local circumstances one would likely get some harvest, however small, and not to completely miss out even when no input is applied as happened under the control plot.

Discussions:

Variability within plots: The soil type on the plot is called *ingusi*. *Ingusi* is yellowish brown to dark brown, clayey soils. It occurs commonly in Emuhaya according to the soil study that was done in February 2002. Striga was very prevalent on plots with high fertility, especially where TSP was applied. This contributed to low harvests on those plots. It was clarified that inorganic fertilisers do not 'bring' or increase striga weed as expressed by few farmers during the discussion. Rather, fertility conditions needed by striga were created on those spots where TSP was used.

Ranking of treatments: Plots were ranked on the basis of: Green leaves – before drying; Thick and long leaves; Height of stalks relative to seed type (hybrid etc.); Bigness of maize, and cobs; Germination rate; Rate of growth, especially after germination, is determinant; Number of cobs on every plant; Number of lines of maize on every cob, especially important in selection of planting seed [12-14 lines (hybrid 513), 16 lines or even more (pioneer usually has one cob with large seeds). Number of lines is relative to type of seed. Also size of every seed matters. Small seeds are good for roasting]; Weight of maize, through estimation by hand and observation.

Farmers used these criteria to rank the various plots. The table below shows results of the ranking. The Table also displays results of previous ranking that had been done and documented two weeks before harvest.

Table 1: Rank of Organic Resources that were used

Rank	**1**	**2**	**3**	**4**
Pre-harvest	FYM	*Tithonia*	*Calliandra*	Stover
Post harvest	*Tithonia*	FYM	*Calliandra*	Stover

Table 1 shows a shift in ranks, between FYM and *Tithonia*. This change came as a result of weighing; maize on *Tithonia* plot was heavier than that on FYM plot. During preliminary ranking, FYM was seen to have had a more positive role in the context of the demonstration trial. Then, the overall aspect was the size and not weight of maize cobs. On the basis of this, FYM had *performed* better because it would result in higher yield.

The order of ranks was respectively similar for plots with organic resources listed above with TSP alone, and TSP and DAP added. It was easier for farmers to tell differences between segments with organic resources only, unlike comparison between those with inorganic fertilisers. Farmers therefore deduced that certain mineral components (i.e.: P) can only be adequately sourced from inorganic fertilisers. P had been unknown to majority of farmers before prior demonstration events were held.

Lessons and conclusions:

- Good harvest (quality and quantity) depends on:
    - Availability of rain, type of rain

    - Timing of planting (recommend that TSBF plant at same time as the majority of farmers to enable them to better compare with and borrow ideas from trial site).
    - Type of soil (recommend that TSBF locate trial sites on each of the major local soil types).
- Appropriate use of high quality resources like *Tithonia* was seen to have a bigger potential locally. However, labour to harvest *Tithonia* was highlighted as a constraint.
- Use of stover as fertiliser was seen as less promising option. Stover is used as fodder and as fuel material, and because it is usually available in small quantities, abandoning it in the field is not very feasible. Other ways to use it more productively should be devised, or to feed it to livestock and to use the resultant dung as FYM.
- The site allowed farmers to better learn how to tell whether plant material is good manure e.g. softness, quick to rot, easy to tear, bitter taste. *Masatsi, mirembe che sisungu* etc.

Observations:

- There is lack of cash to use available technologies, especially because of lack of P in most local soils and the need to buy P-containing fertilisers.
- Farmers' comments that the demonstration plots should be 'large' reflect concerns that local farms display considerable variability in soil quality even over small distances and that it is difficult to extrapolate performance from 3 x 3 m plots. This variability results from concentration of resources on certain sections of the plot – driven by labour shortage, on the basis of what section is more promising. These sites tend to be where there is more fertility and where farmers tend to plant first. There are certain sections (especially near the house) where organic materials are dumped regularly.
- There was much interest in doing more demonstrations; with the current awareness, more farmers are likely to attend and learn from the process.
- Disease and funerals affected attendance in field days at the plot

Soil Biology and Fertility (submitted)

Mucuna pruriens and Canavalia ensiformis legume cover crops: Sole crop productivity, nutrient balance, farmer evaluation and management implications

Delve[1], R.J. and Jama[2], B.
[1]Tropical Soil Biology and Fertility Institute of International Centre for Tropical Agriculture, PO Box 6247, Kampala, Uganda
[2] International Centre for Research in Agroforestry, PO Box 30677, Nairobi, Kenya

Abstract
The high costs of inorganic fertilizers in Uganda limits their use by resource-poor smallholder farmers. There is also little practical knowledge existing in Uganda about the management of herbaceous legume cover crops that often are promoted as low-cost alternatives. Therefore, the effects of a one season sole-crop fallow of *Mucuna pruriens* and *Canavalia ensiformis* legume cover crop on a following maize crop and topsoil N, P and K balances were assessed for 2 seasons in two locations, Osukuru ($0^{o}\ 39^{/}$ N, $34^{o}\ 11^{/}$ E) and Kisoko ($0^{o}\ 43^{/}$ N, $34^{0}\ 06^{/}$ E) of Eastern Uganda. During land preparation, 50 or 100% of the aboveground biomass of Mucuna and Canavalia was manually incorporated into the topsoil (0 to 15 cm depth) using a hand hoe. Mucuna and Canavalia aboveground biomass production was not affected by the initial soil fertility of the sites and produced 6 t ha^{-1} at Osukuru and 7 t ha^{-1} at Kisoko. Incorporation of 50% or 100% of the *in-situ* aboveground biomass significantly increased maize grain by up to 118% and stover yields by up to 75% compared to farmer practice in the first season after incorporation in nearly all treatments. No significant increases in maize grain or stover yields were observed in the second season after application. No significant differences were also observed between 50% and 100% *in-situ* biomass incorporation on maize grain and stover yields, giving resource poor farmers the option of alternative uses for the additional 50% of the biomass, for example, biomass transfer to other parts of the farm, for compost making or for livestock feed. In the first season after incorporation of the legume cover crops, addition of 100% and 50% of the aboveground biomass resulted in a positive nutrient balance for N only. Additions of 100% of the aboveground biomass of either Mucuna or Canavalia were needed for a positive nutrient balance for K, whereas none of the treatments produced a positive balance for P, thus suggesting the need for inorganic P fertilizers additions in order to mitigate depletion in the long run. Farmers had multiple criteria for assessing the different species and used these to select the potential species that fitted within their production systems and production objectives.

Keywords: soil fertility, legume cover crops, Mucuna, Canavalia, nutrient budgets

Introduction
The depletion of much of sub-Saharan Africa's soils through continuous cropping and decreasing nutrient inputs has been widely reported over the last 10 years. All land on the African sub-continent that is classified as very suitable for cultivation was already under cultivation 15 years ago (FAO, 1986). Farmers are increasingly intensifying their agricultural production activities, for example, through the more efficient utilization of animal manures, crop residues and forages and other organic resources. At the same time, use of inorganic fertilizers is decreasing such that organic resources are often the only source of nutrient inputs for farmers (Giller *et al.*, 1997). Resource-poor farmers face difficult decisions over the use of scarce nutrient sources in their production systems. In addition, land constraints force them to trade-off land use in terms of food crop production, fallowing and animal feed supply, amongst others.

Much research has highlighted the benefits of fast-growing legume cover crops (LLCs) to supply nitrogen fixed biologically from the atmosphere to a following non-legume crop in a rotation (e.g. Fujita et al., 1992; Gachene et al., 2000; Giller et al., 1997; Palm et al. 1997). Short growth duration legumes have been used to replenish soil fertility in many parts of Africa (Gutteridge, 1992; Dreschel *et al*., 1996;

Luna-Orea *et al*., 1996; Jama and Nair, 1996; Gachene and Palm, 1999; Rao and Mathuva, 2000; Kayuki and Wortmann, 2001). LCCs refer to the production and incorporation into the soil of leguminous crops that have been grown to enhance the yield of following crops (Lathwell, 1990). Maximum benefit of this approach is seen where the biomass is incorporated into the soil early giving rapid release of nitrogen but farmers often have other priorities in their production system. This can be in terms of a demand for livestock feed, for production of a durable mulch or to control weeds like couch grass. This implies that the farmer may not always manage for the optimal but balance the needs of their farming enterprise. An understanding of how much of the biomass should be incorporated to increase maize yields, where and how this biomass can be produced and what are the alternative uses of the biomass are critical to targeting these legume cover crop technologies.

In Uganda smallholders dominate the agricultural sector with over 90% of crops being produced on household farms averaging less than 2 ha (Appleton, 1998). More than 60% of the land is under cultivation with declining fallow length and increasing periods of continuous cultivation (HASP, 2000). This has greatly reduced crop yields, in addition to increasing pest and weed problems (NARO, 2001). The fallow period has reduced from about 10-12 years of secondary forest fallow in the early 1980s to 3-5 years at present, with the number of crop cycles between a 10-12 year fallow increasing from 2-3 to 4-7 during the same period (Boonman, 1999). Due to these land constraints, the utilization of biomass transfer and legume cover crops was investigated as options for soil fertility management and also in terms of the niches on-farm where they can be grown to fit within the existing production system. Critical to targeting these legume cover crop technologies is an understanding of how much of the biomass should be incorporated to increase maize yields, where and how on the farm this biomass can be produced, what are the alternative uses of the biomass and what are the opportunities and constraints to technology adoption identified by farmers.

The objectives of the study were, (i) to evaluate the effects of *Mucuna pruriens* and *Canavalia ensiformis* on maize yields, and nutrient balances, (ii) to determine the effects of different management options for Mucuna and Canavalia (full vs. partial incorporation of above-ground biomass into the soil) in farmer-managed trials in maize-based system of eastern Uganda and (iii) use farmer evaluations of the technologies to assess their potential adoption and to identify areas of adaptive research.

Materials and Methods

Site description

Farmer managed on-farm experiments were conducted on five farmers' fields in each of two sub-counties (Kisoko and Osukuru) in Tororo District, Eastern Uganda. Both sub-counties are 1000-1200 m.a.s.l., receive bimodal rainfall of 1000-1200 mm per year and maize, groundnuts and cassava are the main crops. The two sites differ in their geographical position with Kisoko being about 20 km North of Osukuru with soil fertility and rainfall, particularly the chance of extended dry spells increasing as you go North. The soils are generally sandy clay loams (Kandiusalf) and have good pH and are generally low in organic C, N and P. The sites significantly differ in their clay content (16.3 vs. 31.3) and total soil N (0.05 vs. 0.11) for Kisoko and Osukuru respectively with all other parameters being non-significant (Table 1).

Experimental design

Following the harvesting of an unfertilised maize crop, Mucuna (75 cm by 60 cm) and Canavalia (75 cm by 30 cm) were planted as sole crop fallows for one season. No amendments were added to the soil at the time of legume planting so that the legume cover crops would be produced under farmers' conditions. At the beginning of the next season the legume cover crops LCC were cut, allowed to wilt for five days and incorporated into the soil at either 50% or 100% of the *in-situ* produced biomass. The treatments were as follows: 1) absolute control, 2) fertilized control, with P and K application, 3) 100% of above-ground Mucuna biomass incorporated, 4) 50% of above-ground Mucuna biomass incorporated, 5) 100% of above-ground Canavalia biomass incorporated and 6) 50% of above-ground Canavalia biomass incorporated. A basal application of TSP (80 kg P ha^{-1}) and Muriate of potash (60 kg K ha^{-1}) was broadcast and incorporated to a depth of 15 cm in all plots except treatment one. Farmers managed the experiments and conducted weeding and other management practices as they would for their own farm.

Experimental design – planting and harvest

A RCBD was used with five replicates, with each of the five farms acting as a replicate. Maize (hybrid Longe1) was sown at a spacing of 0.75 m by 0.25 m, with two seeds per hole and was thinned to one seed per hole after two weeks (53,200 plants ha^{-1}). Plots were kept weeded during the farmers normal weeding operations. At physiological maturity net plots (3.75 m by 4 m) were harvested and the weight of maize stover, grain and cobs recorded. Sub-samples were collected, chopped and dried at 70°C for 48 hours. After harvest, all plots were cleared of weeds and crop residue and hand ploughed. In the following two seasons maize (hybrid Longe1) was sown to investigate the residual benefits of the LCCs.

Soil and plant analysis

Soil samples (0-15cm) were collected at the beginning of the experiment and bulked by sub-county for analysis. Samples were analysed for pH (water), Total N (Kjeldahl digestion), Total C (Walkley-Black), extractable P (Olsen and Sommers, 1982), macronutrients (extracted in NH_4Oac; atomic absorption spectrophotometer) and texture. LCC plant samples were analysed for total N (Kjeldahl) and total P and K (Kjeldahl; atomic absorption spectrophotometer; Parkinson and Allen, 1975).

Farmer participatory evaluation

Farmer participatory evaluations were conducted using open questions and probing questions. Qualitative data was also collected on farmer criteria used in selection of LCCs technologies and on innovations made by farmers.

Statistical analysis

Data were analysed by the SAS General Linear Models procedure (SAS Institute Inc., 1988). ANOVA was used for mean separation and significance is reported at the P<0.05 level.

Results

LCC biomass production and nutrient content

Comparative analysis of the macronutrient content of the LCC's shown there was only a significant difference in the plant species for their Calcium contents (Table 2). There were no significant differences in location or in the species by location interaction. Similarly, there were no significant species or location differences in the biomass production of the two LCCs, nor in the amount of N applied in the experimental design. The amount of biomass produced was not significantly different but for both locations Mucuna and Canavalia exceeded 6 t DM ha^{-1} and 7 t DM ha^{-1} in Kisoko and Osukulu, respectively.

Maize production

There was no significant difference between the sites except for stover production in the first season (Table 3). Therefore data was combined for further statistical analysis. No significant increases between the control and the positive control (with P and K addition) were observed indicating that the site was N limiting and not P or K deficient.

In the first season, at both sites, all treatments (except 50% incorporation of Canavalia biomass in Osukulu) gave significantly higher grain and stover yields compared to the control (Table 3). In all cases where biomass production was significantly higher than the control, the yield increase was more than 100% higher than the control treatment. Incorporation of 100% rather than 50% of the biomass produced in the plot did not significantly increase maize grain yields compared to the control (Table 3). In the second residual season no significant differences were observed for maize grain and stover production between treatments. Combined yields over the two seasons showed significant increases in maize grain yield for all treatments except for maize stover production for maize grain with the 50% Canavalia incorporated treatment. The total dry matter yield of grain and stover over the two seasons was highly significant ($P<0.001$) for all treatments (Table 3).

Nutrient balance

The farmers normal practice of growing maize without additions of organic or inorganic fertilizers not surprisingly resulted in negative nutrient balances for N, P and K (Fig. 1). In the first season after incorporation of the LCCs, addition of both 100% and 50% of the aboveground biomass reversed this negative nutrient balance for N only. Additions of 100% of the aboveground biomass of either Mucuna or Canavalia were needed for a positive nutrient balance for K, whereas none of the treatments produced a positive balance for P (Fig. 1). Nutrient balances were not calculated for the residual seasons as there were no significant differences in maize grain and stover yields.

Farmer participatory evaluation

Farmers assessment of the LCCs species revealed many positive and negative aspects for each species (Table 4). Many positive criteria were mentioned by farmers that were expected for these species, for example, improved soil fertility, provides livestock fodder. More interesting from the research prospective were the negative aspects. For example, Mucuna and Canavalia were notably disliked because their seeds are not edible yet they looked very attractive to eat, and are produced in large numbers, even in dry seasons. Mucuna was further disliked for its unsuitability for intercropping and because it can harbour snakes if planted near the homesteads.

Discussion

Legume biomass production

The lack of significant differences in biomass yield of the mucuna and canavalia (Table 2) at the sites in spite of Kisoko being more deficient in N (Table 1) would suggest that similar BNF among the two species at both sites. Biomass dry matter productivity averaging 6.8 t DM ha^{-1} for Mucuna and 7.0 t DM ha^{-1} for Canavalia in six months compares with other reported data. For *Mucuna pruriens* other authors have reported varying sole crop one-season biomass production figures. Mucuna produced 1.3-3.50 t DM ha^{-1} and in some cases up to 9 0 t DM ha^{-1} in one season in Rwanda (Drechsel, *et al.*, 1996); an average of 5.7 t DM ha^{-1} across five sites in Malawi (Kumwenda and Gilbert, 2000) and an average of 4-7 t DM ha^{-1} from sites across Kenya (Dyck, 1997).

Comparative data for Canavalia ensiformis has been much harder to find. Gachene et al. (2000) report production figures of 3-6 t DM ha^{-1} in six months. These different production figures are due to differences and variations in soils, rainfall, seasons and management of the legumes for the different citations.

Grain and stover yield

All significant treatments increased maize grain yields by between 106% and 118% in the first season, these yield increases more than compensate the farmer for the loss of one seasons production of maize whilst the legume cover crop is being grown. Kumwenda and Gilbert (2000) reported maize grain yield increases averaging 180% following Mucuna incorporation in five sites across Malawi. Whilst other studies have not reported such yield increases of above 100% and therefore did not find that the extra maize yield compensated for the land being out of production for one season (Drechsel, *et al.*, 1996). Also, work in Uganda work with different legumes found that maize yield increases varied by season and legume species but on average did not consistently return yield increases of above 100% (Fishler, 1997; Tumuhairwe, 2001).

Although the grain and stover results were not significant in the second season it has to be remembered that farmers under their own conditions, with individual farmers as replicates, conducted this work. Therefore, the level of error would be expected to be higher than a replicated on-station or a replicated on-farm experiment. The second season results were significant ($P<0.10$) for maize grain and stover yield, giving the farmer a two-season benefit.

Where the yield increases do not compensate for the loss of maize production during the season of LCC production there is unlikely to be any adoption in areas of high population density where there is a high demand every season for cropping land. The advantages of LCC can best be utilized where land is out of production due to low fertility or high pest/disease pressures or where it would be left in a natural fallow system. In addition, the significant increases in associated maize stover provide increased options for the farmers. The extra stover can be used in livestock feed or bedding, soil erosion control, compost making or mulching the banana crop.

Another very important conclusion of this work is that incorporation of 50% or 100% of the *in-situ* produced biomass produces a maize grain and stover yield that is not-significantly different from each other. This again then provides the farmers with increased options for their resource management. For example, this would allow the farmer to produce the biomass in one place and to apply the biomass over twice the area for maize production. Alternatively they might want to use 50% for incorporation and the remaining 50% for livestock feed, sale to other farmers or to produce hay for dry season feed. Increasing the resource management options and therefore the production options of the farming enterprise is critical where land sizes and fallow areas are small and little area is available for non-food crop production and where cash is not-readily available to buy inputs for crop and livestock production.

Nutrient balances

The N fixed by LCCs during the fallow period may not a net addition to the system if increases in the following crop yields removes more N than is added by the legume. The large applications of N in the LCC biomass (Table 2) will be exposed to leaching as decomposition occurs, especially during the tropical storms that characterise the beginning of the rainy season. Much work has been conducted on decomposition and nutrient release rates for legumes, with different rates being reported. For example, more than 50% of N, P, K and Mg from Desmodium and Pueraria being released in four weeks (Luna-Orea et al., 1996); 60% of N from Leucaena and Senna in the first four weeks (Jama and Nair, 1996). Drechsel, *et al.* (1996) concluded that as sowing starts immediately after the first lasting rainfall, it is impossible to optimize the time of green manure incorporation before sowing. This may be true but there are management options available to reduce leaching of N and increase synchrony of release with demand. For example, incorporation of sorghum straw and green manures significantly delayed and reduced leaching of nitrate, by around 30%, of the mobilized legume nitrogen (Hagedorn, 1995 in Dreschel *et al.* 1996). Similarly, other nutrient balance studies in Uganda have reported negative balances for a range of cropping systems (e.g. Bekunda and Woomer, 1996; Wortmann and Kaizzi, 1998).

Farmer participatory evaluation

There was no doubt among the farmers that the LCCs technologies work and were better than the traditional practice as far as improving soil fertility was concerned. In terms of costs, it was reported that the use of LCCs and biomass transfer species offered a low input technology to the farmers, as most of them could not afford use of inorganic fertilizers especially on the low value crops like maize. Farmers evaluation however raised many concerns over the adoptalibility of the technology. Farmers observed that the use of LCCs required a substantial amount of land for production and for sole crop production this is left under fallow with no food crop being produced, high labour for clearing and ploughing in the vegetation, and patience in attaining the results (Table 4). In addition, the single purpose use of the LCC was mentioned as a negative aspect in terms of the adoption of the technology.

Conclusion

In the on-farm experiments reported here in two areas of Uganda, the use of *Mucuna pruriens* and *Canavalia ensiformis* significantly increased the following maize yields in the first season ($P<0.05$) and in the residual season ($P<0.10$). Farmer evaluations of the technology highlighted some negative aspects of this technology, for example, it needs increased management by the farmer as well as increasing the labour input into the cropping system, in addition, many farmers do not have the opportunity to leave land fallow for one season to produce the LCC. This method of soil fertility improvement is just one of the many options available to farmers and the exact production system the farmer develops will depend on many other issues, for example, access to inorganic fertilizers, the need for firewood, livestock feed or grain legume production. Farmer evaluations identified research gaps with this technology that are now being investigated in further on-farm experimentation. LCC species, however, still remain a strategic opportunity for the many farmers that have no access to fertilizers or animal manures and who have available land.

References

Appleton, S. 1998. Changes in Poverty in Uganda (1992-1996), WPS/98-15, Centre for the Study of Africa Economies, University of Oxford, UK.

Bekunda, M. A., and Woomer, P. L. (1996). Organic resource management in banana-based cropping systems of the Lake Victoria Basin, Uganda. Agric, Ecosys and Environ 59: 171-180.

Boonman, J.G., 1999. Green- and Organic manures in mixed farming systems of East Africa. Boma Consult, Javastraat 103, NL 2585 AH The Hague, The Netherlands. pp.56

Drechsel, P., Steiner, K. G., Hagedorn, F. 1996. A review of the potential of improved fallows and green manure in Rwanda. Agroforestry Systems 33: 109-136

Dyck, E. 1997. Screening legumes for potential soil productivity improvement in Kenya: Kenyan legume research network. Poster presented at Green Manure Cover Crops conference in Santa Catarrina, Brazil, 6-12 April 1997.

FAO 1986. African agriculture: The next 25 years. Annex II. The land resource base. Rep. No. ARC/86/33. F.A.O., Rome.

Fischler, M. 1997. Legume green manures in the management of maize-bean cropping systems in eastern Africa with special reference to crotalaria (C. ochroleuca G. Don.).

Ph.D. thesis, Swiss Federal Institute of Technology, Zurich.

Fujita, K., Ofosu-Budu, K. G., Ogata, S. 1992. Biological nitrogen fixation in mixed legume-cereal cropping systems. Plant and Soil 141: 155-175

Gachene, C. K. K., Palm, C. A., Mureithi, J. G. 2000. Legume cover crops for soil fertility improvement in the eastern Africa region. Report of an AHI workshop, 18-19th February 1999, Nairobi, Kenya, pp24

Giller, K.E., Cadisch, G., Ehaliotis, C., Adams, E., Sakala, W.D., Mafongoya, P.L., 1997. Building soil nitrogen capital in Africa. In: Buresh, R.J., et al. (Eds.) Replenishing soil fertility in Africa. SSSA Spec. Publ. 51. SSA, Madison, WI, USA, pp. 151-192.

Gutteridge, R. C. (1992). Evaluation of the leaf of a range of tree legumes as a source of nitrogen for crop growth. Exper Agric 28: 195-202.

HASP, 2000. Household Agricultural Support Programme. A Baseline Survey Report on Status of Service Delivery. Tororo Local Government, Uganda. pp 32.

Hagedorn, F. 1995. Organische Dungung in Sud-Rwanda – Einfluss auf Kohlenstoff und Nahrstoffdynamik. Masters thesis, University of Bayreuth, Germany, 99 pp.

Jama, B., Palm, C.A., Buresh, R.J., Niang, A., Gachengo, C., Nziguheba, G., Amadalo, B. 2000 Tithonia diversifolia as a green manure for soil fertility improvement in Western Kenya: A review. Agroforestry Systems 49: 201-221.

Jama, B., Nair, P. K. R. 1996. Decomposition and nitrogen mineralization patterns of Leucaena leucocephala and Cassia siamea mulch under tropical semi-arid conditions in Kenya. Plant and Soil 179: 275-285

Kayuiki, K. C. and Wortmann, C. S. 2001 Plant Materials for Soil fertility Management in Subhumid Tropical Areas. Agron Journal 93: 929-935

Lathwell, D. J. 1990. Legume green manures: Principles for management based on recent research. Tropical Soils Bulletin No 90-01. Soil Management Collaborative Research Support Program, North Carolina State University, Raleigh, NC. pp 30

Luna-Orea, P., Wagger, M. G., Gumpertz, M. L. 1996. Decomposition and nutrient release dynamics of two tropical legume cover crops. Agron. Journal, 88: 758 - 764

NARO, 2001. Medium Term Plan 2001-2005: Responding to Research Challenges for the Modernisation of Agriculture**.** National Agricultural Research Organisation, Entebbe, Uganda, February 2001.

Olsen, S.R., and L.E. Sommers. 1982. Phosphorus. p. 403-430. *In* A.L. Page, R.H. Miller, and D.R. Keeney (ed.) Methods of soil analysis, part 2 - chemical and microbiological properties. 2nd Edition. ASA and SSSA, Madison, WI.

Palm, C.A., Myers, R.J.K, Nandwa, S.M., 1997. Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. In: In: Buresh, R.J., Sanchez, P.A., Calhoun, F. (Eds.), Replenishing soil fertility in Africa, SSSA, American Society of Agronomy, Madison, Wisconsin, USA, pp 193-217.

Parkinson, J.A., and S.E. Allen. 1975. A wet oxidation procedure suitable for the determination of nitrogen and mineral nutrients in biological materials. Comm. Soil Sci. Plant Anal. 6: 1-11

Rao, M. R. and Mathuva, M. N., 2000. Legumes for improving maize yields and income in semi-arid Kenya. Agric, Eco and Environ, 78: 123-137

SAS Institute Inc. 1988. SAS Users Guide, Cary, NC, USA.

Tumuhairwe, J. B., 2001. Effect of short-duration *Crotalaria grahamiana* and *Mucuna pruriens* fallows on soil productivity in south-eastern Uganda. M.Sc. thesis, Makerere University, Kampala, Uganda.

Wortmann, C. 1998 Some best bet options for integration of legumes into farming systems of mid-altitude areas of Uganda. CIAT Extension Brochure

Wortmann, C. S., and Kaizzi, C. K. (1998). Nutrient balances and expected effects of alternative practices in farming systems of Uganda. Agric, Eco and Environ 71: 115-129.

Acknowledgments

We are grateful to various investors that have provided funds to the project: DFID through the SWNM program; Rockefeller Foundation; Uganda SFI program with support from RELMA, the SFI under SPAAR in the World Bank. A special acknowledgement goes to the staff of Africa2000 Network in Tororo for managing the field trials and to the many farmer groups we are working with.

Table 1: Soil characterisation in Kisoko and Osukuru sub-counties in Eastern Uganda

Location	pH	Total N	Total C	Total P	Ca	Mg	K	P	Clay	Sand	Silt
		(%)	(%)	(%)	-----cmol g^{-1}------			(ppm)	----------%---------		
Kisoko	6.80	0.05	0.66	0.02	3.77	0.80	0.26	7.97	16.3	64.7	19
Osukuru	6.11	0.11	1.32	0.10	6.46	1.76	0.37	33.2	31.3	51.1	17.6
$LSD_{0.05}$	ns	0.04	ns	ns	ns	ns	ns	ns	10.6	ns	ns

Table 2: Legume cover crop nutrient analysis, biomass production and amounts of N added in the treatments for the two sub-counties.

Location name	Total N (%)		Total P (%)		Ca		Mg		K		Biomass (kg DM ha^{-1})		Applied-N (kg ha^{-1})	
	Can[1]	Muc[2]	Can	Muc	Can	Muc	Can	Muc	Can	Muc	Can	Muc	Can	Muc
Kisoko	2.9	2.4	0.13	0.20	4.2	1.6	0.40	0.35	1.0	1.2	6626	6111	190	153
Osukuru	3.1	2.5	0.27	0.20	4.8	1.3	0.50	0.25	1.5	1.4	7435	7502	228	188
LSD (0.05)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	Significance level													
Plant species	0.18		0.97		0.0005		0.13		0.92		0.86		0.37	
Location	0.67		0.32		0.81		1.00		0.23		0.42		0.39	
Location * Species	0.82		0.32		0.50		0.31		0.65		0.83		0.98	

[1] Can=*Canavalia ensiformis*

[2] Muc = *Mucuna pruriens*

Table 3: Maize grain and stover yields following application of Mucuna and Canavalia in Osukuru sub-county, Tororo District

Treatment description	Grain Crop1[1]	Grain Crop2[2]	Grain Crop1+Crop2	Stover Crop1	Stover Crop2	Stover Crop1+Crop2	Sum Stover + Grain, all crops
	----------	----------	----------	t DM ha^{-1}	----------	----------	----------
100% Canavalia	3.5	3.3	6.9	4.0	4.5	8.6	15.5
100% Mucuna	3.7	3.7	7.3	4.2	4.3	8.2	15.6
50% Canavalia	3.0	3.3	6.4	3.5	4.2	7.4	13.8
50% Mucuna	3.5	3.3	6.9	4.0	4.1	8.0	14.9
Control F P	1.7	2.2	3.9	2.4	2.9	5.0	8.9
Control P K	2.3	2.8	5.1	2.7	3.6	6.3	11.5
	Significance level						
Site (0.05)	0.18	0.62	0.09	0.01	0.72	0.25	0.12
Treatment (0.05)	<0.0001	0.08	0.0001	0.02	0.07	0.03	0.001
Site $LSD_{0.05}$	ns	ns	ns	0.75	ns	ns	ns
Treatment $LSD_{0.05}$	0.73	ns	1.40	1.18	ns	2.08	3.11

[1] Crop1 = the first crop after incorporation of the legume cover crop
[2] Crop2 = the second crop after incorporation of the legume cover crop

Table 4. Farmers' assessment of the LCCs species for soil fertility improvement

LCC/shrub	Positive aspects	Negative aspects
Mucuna pruriens Local name: none	✓ Improves soil fertility ✓ Suppress weeds effectively ✓ Produce high biomass ✓ Quick maturing	x Not edible x Not good for intercropping (Climbs the crops) x Requires high labour for clearing and incorporation x Can harbour snakes if planted near the home
Canavalia ensiformis Local name: Yathipendi (medicine for banana) or Akengu ka angu (trap for the hyena)	✓ Improves soil fertility ✓ Has fodder value ✓ Suppresses weeds ✓ Easy to multiply (high seed production) ✓ Good for intercropping	x Not edible x Difficult to incorporate

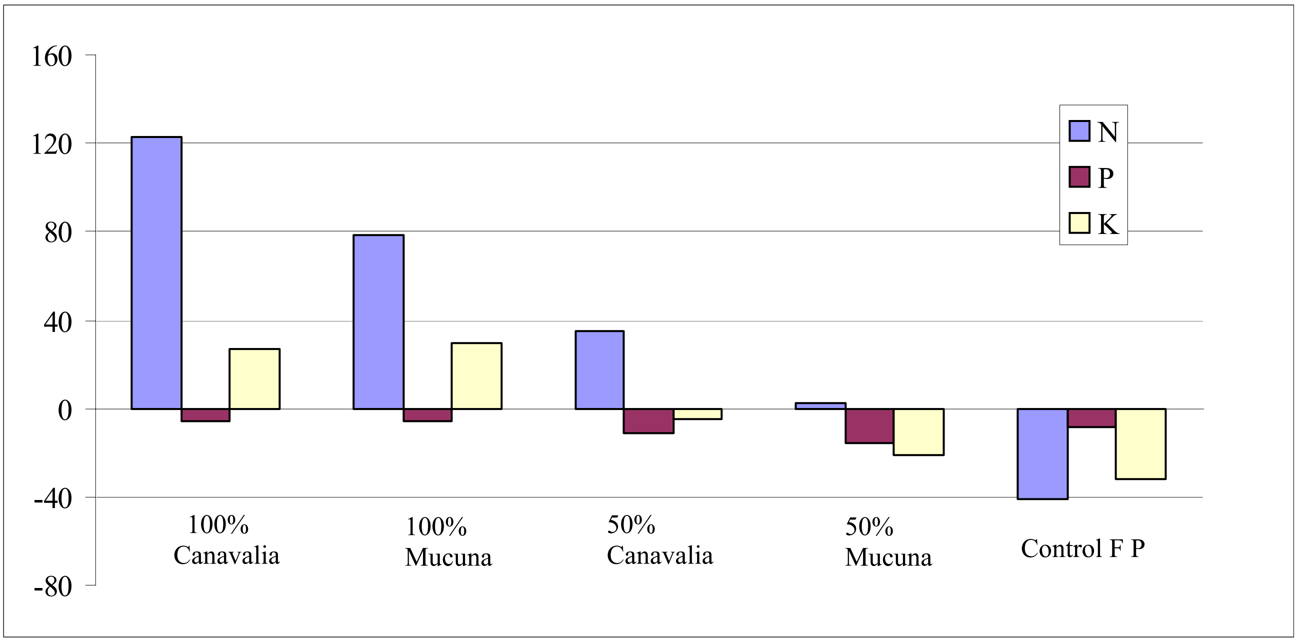


Figure 1: Macro-nutrient balance for maize grain and stover production following incorporation of 50% and 100% of the above-ground biomass of Mucuna and Canavalia legume cover crops

Submitted to Experimental Agriculture

Farmer participatory evaluation of legume cover crop and biomass transfer technologies for soil fertility improvement using farmer criteria, preference ranking and logit regression analysis

Nyende, P. and Delve, R. J
Tropical Soil Biology and Fertility Institute of International Centre for Tropical Agriculture, PO Box 6247, Kampala, Uganda

Summary
Six species, *Canavalia ensiformis*, *Crotalaria grahamiana*, *Dolichos lablab*, *Mucuna pruriens*, *Tephrosia vogellii* and *Tithonia diversifolia* were evaluated as potential species for soil fertility replenishment in on-farm adaptive trials, farm visits and field days in Tororo District, eastern Uganda. Farmers used multiple criteria for assessing and selecting potential species that fitted within their production systems and production objectives. Farmers also adapted the technologies to allow for local opportunities and constraints. A preference ranking and logit regression analysis of probabilities of acceptance of the species conducted in 19 farmer groups showed that Tithonia had high, Mucuna and Crotalaria intermediate and Lablab and Tephrosia low probabilities of being accepted or adopted. The evaluations showed that whilst technologies need to be adapted, a single use technology had little chance of large-scale adoption. This paper highlights adaptations/innovations by farmers and opportunities for participatory action research targeting farmers' production objectives.

Introduction
In the recent past the image of agricultural and environmental crises in sub-Saharan Africa (SSA) has become increasingly common. Soil erosion and soil fertility loss are considered to be undermining the productive capacity of the agricultural systems (Giller *et al*., 1997; Sanchez *et al*., 1997; Smaling *et al*., 1997). Within this environment smallholder farmers use a wide range of agro-ecological management techniques, resource management practices and production strategies specific to their environment to minimise risk, cope with change and shocks and to manage the environment (ecological, social, economic etc) they operate within. These can include, for example, agricultural intensification, expanded market-orientation, increased capital and labour investment. Alternatively, farmers have been found to exploit their resource base where constraints are too high, the returns to investment are too low (even negative, as when staple commodity prices plummet during bumper harvests), or environmental conditions too erratically variable for secure investment.

Since 1998, a number of collaborating partners working in Tororo district through an adaptive research project, the Integrated Soil Productivity Initiative Through Research and Education (INSPIRE) have been evaluating a range of soil fertility management options with farmers. The collaborators in the INSPIRE initiative which began with the main objective of introducing, developing, on-farm testing and disseminating improved soil fertility management technologies to address the alarming soil productivity problems in Tororo district include, Africa 2000 Network (A2N), Appropriate Technology (Uganda), International Centre for Tropical Agriculture (CIAT), Tororo district Departments of Agriculture and Extension, Farmer group representatives, Food Security and Marketing (FOSEM) project, International Centre for Research in Agroforestry (ICRAF), National Agricultural Research Organization (NARO), Makerere University, Tropical Soil Biology and Fertility Programme (TSBF), and Uganda National Farmers Association (UNFA).

During the participatory diagnostic stage of the project, use of legume cover crops and biomass transfer species to improve soil fertility were identified as potential technologies due to their cost effectiveness, appropriateness, simplicity, and multi-purpose nature in meeting the needs of resource poor farmers. In smallholder farming systems of the tropics and sub-tropics, increasing use is being made of legume cover crops (LCCs) and biomass transfer (BT) species as sources of nutrients, particularly nitrogen, for crop growth (Dreschel, *et al*., 1996; Rommelse, 2001; Buresh and Niang, 1997). This is in part due to the increasing cost and variable availability of inorganic fertilizers at the village level. Less than 5% of the farmers in eastern Uganda use mineral fertilizers and this is usually on an irregular basis (Mirro *et al*., 2002). In addition, traditional natural fallow is no longer practiced due to the decreasing farm sizes and the availability of animal manure is limited by decreased cattle numbers (Mirro *et al*., 2002).

Six species, *Canavalia ensiformis*, *Crotalaria grahamiana*, *Dolichos lablab*, *Mucuna pruriens*, *Tephrosia vogellii* and *Tithonia diversifolia* were first introduced in two sub-counties of Kisoko and Osukuru. Much work has been conducted on the biophysical performance of these legume cover crop and biomass transfer technologies since 1998 in Tororo (Tumuhairwe, 2002a; Tumuhairwe 2002b; Delve and Jama, 2002b). Beyond agronomic evaluation it is essential to identify opportunities and constraints of each introduced technology, conduct assessments to understand farmers' actual use and management of the technologies, perceived benefits, farmers ideas and perceptions, innovations, and problems and solutions in the use of the technologies (Douthwaite *et al*., 2002; Bellon, 2001). To address this, a farmer participatory evaluation of these technologies was therefore initiated in December 2001 and January 2002 (after seven seasons) with the main objective of providing a feedback on the performance of the technologies. This paper reports on the findings and analysis of participatory evaluations by 19 farmer groups, involving 234 individual farmers (92 male, 142 female), who had been evaluating through on-farm adaptive research the performance of legume cover crops (LCCs) and biomass transfer (BT) species for soil fertility improvement.

Materials and methods

Developing qualitative farmer criteria for preference ranking

Farmer participatory evaluations were conducted using open questions, probing questions and preference matrix ranking. The farmers who participated in the evaluation exercise were purposively selected and belonged to a farmer group who had at least five seasons experience experimenting with LCCs and biomass transfer species. Focus group discussions were used to elicit farmer criteria (negative and positive) used in selection and preference ranking of LCCs and biomass transfer technologies.

Quantitative analysis of ranking data

From the preference rank list of the six species from each group, a frequency table was drawn up of the number of times each species was ranked in a certain position, where one is the most and six is the least preferred species. From this frequency table, the probability of a particular species being ranked in a certain position was calculated, where,

Probability = frequency / total number of observations …………….(1)

A further calculation was done to produce the cumulative probability of each species, that is, the sum of the probability for that rank and the probabilities for all previous ranks. Further data analysis was done using a logit regression with a Chi-squared test (at 15% level significance) using the Logistic Preference Ranking Analysis Tool for evaluating technology options (Hernandez-Romero, 2000). The preference ranking logic regression allowed the statistical analysis of qualitative preference ranking data and allowed a further separation of species into those likely to be adopted or not.

Innovations with the technologies

During the focus group discussions and evaluation process, farmers were asked to list the innovations (i.e. what they did differently from the initial aim of the demonstration) for the different species and how this differed from what they had seen in the demonstration sites

Results

Farmer evaluation of options

Farmers' evaluation of the LCCs and biomass transfer species revealed many positive and negative aspects for each species (Table 1). Some of the positive criteria were, improving soil fertility and providing livestock fodder. More interesting from the research perspective were the negative aspects. For example, Mucuna and Canavalia were notably disliked because their seeds are not edible yet they looked very attractive to eat, and are produced in large numbers even in dry seasons. Mucuna was further disliked for its unsuitability for intercropping and because it can harbour snakes and wild cats if planted near the homesteads. The pest problem on *C. grahamiana* was cited as a serious set back as the caterpillars that eat the leaves and flowers scare the women and children. Tephrosia also was cited as having a pest problem that leads to flower abortion and hence poor seed formation. Lablab was reportedly having a problem of seed formation while Tithonia was feared to be a potential weed if not managed properly.

Criteria for evaluating the LCCs and biomass transfer species

Criteria for ranking the species' performance were developed and a summary of criteria is given in Table 2. Each group developed its own criteria for ranking, however the four most important criteria for all 19 groups were, yield increase of crop after fallow or intercrop, soil fertility increase, multiple uses of the LCC or BT species and ability to control weeds.

Farmer preference ranking of the LCCs and BT species

Based on the criteria developed with the farmers a ranking analysis tool was used to rank the six species. There was little variation among groups in the rank orders but the overall rank order from the most to the least preferred was Mucuna, Canavalia, Crotalaria, Tithonia, Tephrosia and Lablab (Table 3). Since farmers first experienced most of the LCCs and BT species in the course of the present study, the ranks assigned to some species are a preliminary hint to their adoption potential.

Distribution of probabilities of acceptance of LCCs and biomass transfer technologies

Table 4 shows the number of times a particular species is ranked in a certain position (acceptance frequencies). For example, Mucuna was ranked in position one seven times, five times in position two, zero times in position three, etc by all the 19 farmer groups. Plotting cumulative probability against the ranking position allows a graphical representation of the acceptance of a technology option (Figure 1). The analysis of cumulative probability versus ranking position showed that for the 19 groups, Mucuna, Crotalaria, Canavalia and Tithonia all had positive intercepts on the y-axis (probability of acceptance), i.e. high probability of being ranked highly by farmers and Tephrosia and Lablab had negative intercepts and are therefore likely to be rejected by the farmers and not adopted (Figure 1; Table 5).

A higher slope with a positive intercept on the y-axis means that the technology option has a high probability of being ranked highly by farmers, indicating that they have characteristics that meet farmers needs and therefore should be taken into account while promoting the species. In addition, they are more likely to be adopted. In contrast, a high slope with a negative intercept shows a likelihood of that technology option being ranked often in the last places of the ranking and hence is not liked by farmers.

Statistical analysis of the logit regression

Further analysis of the slope of the regression line and using a Wald chi-square test showed that Mucuna and Crotalaria have low slopes of 0.04 and 0.08 respectively, but with positive intercepts indicating intermediate probabilities of acceptance (Table 5). Canavalia and Tithonia with high slopes of 0.10 and with positive intercepts (differs statistically) have high probabilities of acceptance in accordance with the model used in this analysis. On the other hand Lablab and Tephrosia with high slopes but with negative intercepts indicate low probabilities of acceptance. The analysis of Canavalia was not significantly different ($P<0.15$) to zero (i.e. there is no difference between the use or no use of the species), indicating likelihood for non-acceptance by the farmers.

Farmer innovations with the LCC and biomass transfer species

Some farmers indicated that they had tried using the LCCs and biomass transfer species in a different way besides what the researchers had demonstrated during the trials. The ways in which the farmers adapted and adopted the technologies are shown in Table 6. Farmers also invented their own names for some species of the LCC and biomass transfer species they were using (Table 1). Canavalia was locally known as ‘Yathipendi’ meaning ‘medicine for banana’ and another group that was dominated by old men identified it as ‘Akengu ka Angu’ meaning ‘trap for the Hyena’. Tephrosia was locally known as ‘Yathi fuuko’ (medicine for mole rat) or ‘Yathirechi’ (medicine for fish). *Tithonia diversifolia,* was locally referred to as ‘Mawuwa’ but with no particular meaning attached to the name. Mucuna and Crotalaria were known by their botanical names as obtained from the researchers. Farmers’ identification of the LCC and biomass transfer species by such names reveals several issues.

Discussion

Farmer evaluation of options

When faced with many options, framers face complex decisions. This study shows that farmer’ assessment of the LCCs and biomass transfer species revealed many positive and negative aspects for each species. The criteria used for selection and the farmers’ innovations revealed new research constraints and opportunities. For this farming system, highlighting potential new areas of research, for example, research into suitable niches for the best-bet species (Muhr *et al*., 2001) and/or identifying varieties that can be consumed by humans, e.g. dual-purpose grain legumes (Ecoregional Alliance, 2001) are important for enhancing the adoption of a technology. This study also confirms the labour constraint with use of LCCs and BT species for soil fertility improvement and therefore a serious constraint in the adoption of the technology (Obonyo, 2001; Tumuhairwe *et al.*, 2002b). Addressing these identified constraints will ensure that future research is relevant to the needs of the farmers and therefore have a higher chance of being adopted.

There was no doubt among the farmers that the LCCs technologies work and were better than the traditional practice as far as improving soil fertility was concerned. In terms of costs, it was reported that the use of LCCs and BT species offered a low input technology to the farmers, as most of them could not afford use of inorganic fertilizers especially on the low value crops like maize. Farmers however, observed that the use of LCCs and BT species required a substantial amount of land for production and for sole crop production which is left under fallow with no food crop being produced, high labour for clearing and ploughing in the vegetation, and patience in attaining the results.

The fact that food production is the key priority of the farmer means that they are very risk averse and need to produce a food crop every season, so investing present resources in the possibility of future increased production is not necessarily interesting to farmers. As an adaptive research farmer commented, ‘*Its better to have even one gorogoro tin of maize from a depleted field that was planted with maize than to be guaranteed no maize at all this season by planting a cover crop we can’t eat*’ (Ramisch, pers. Comm..). Despite these constraints, farmers conducting trials on legume cover crops for soil, water and nutrient management in Malawi expressed that through learning-by-doing and doing-by-learning, they learnt that there are some legume cover crops such as Mucuna, pigeon pea, tephrosia, soybeans ground nuts and common beans that improve soil fertility and at the same time be used as a green manure and/or food (Marra *et al*., 2002; Douthwaite *et al*., 2002). Recent experiences with farmers using simulation model discussions further provide evidence of the role risk, uncertainty and learning play in the process of adopting/adapting new technologies (Braun, 2001).

Statistical analysis of the logit regression

This study shows that farmers can make use of more than one LCC or BT technology depending on their production objectives and resource endowments. They can observe, compare and decide on alternatives, using criteria drawn from their own experiences. Findings from case studies in Malawi and Zimbabwe also indicate that a broad range of options rather than blanket recommendations (as offered by government extension services) can increase adoption and improve productivity and food security (Marra *et al*., 2002).

The logit preference ranking analysis tool used in this study helps to explain decisions on acceptance or rejection of the technology, based on the criteria and/or farmer group used to choose one technology rather than another. The tool further allows the statistical analysis of qualitative data and a detailed separation of technologies into those likely or unlikely to be accepted, something that is not possible through ranking alone. Information generated from this tool provides essential feedback to the technology development process. This tool has been used to conduct participatory evaluations of cassava, potato, beans and maize varieties in Ecuador and Colombia (Hernandez-Romero, 2000).

Implications of participatory evaluation on the research process

In the process of technology change and innovation it is essential to understand not only the farmers perceptions but also those of all the stakeholders involved in the research process (Douthwaite *et al.*, 2002; Bellon, 2001). Therefore, the next stage in this adaptive research process involved the systematisation of information, detection of knowledge gaps, and the identification of potential research questions during follow-up community meetings attended by the farmers, extension agents, NGO and CIAT staff. During these meetings the results of the participatory evaluation were discussed and this led to the identification of new research questions that need to be addressed through strategic on-station research; adaptive research conducted by National partners and adaptive research conducted by farmers. The different partners then agreed on the way forward to address these issues:

Key farmers to conduct adaptive research on behalf of the community. These farmers will establish a range of experiments, and will be responsible for monitoring the experiments and reporting back to the whole community on the results.

Applied research questions to be addressed by National agricultural research partners, through an array of methods from on-station research to on-farm research.

Strategic research questions to be addressed by CIAT, TSBF, and other partner international research institutes through an array of methods from, strategic on-station research to on-farm research.

In this study, LCC and BT technologies that were introduced to farmers for soil fertility replenishment have been adapted and are being improved through participatory evaluations to include a much wider range of production objectives. The evaluations showed that whilst technologies need to be adapted, a single use technology had little chance of large-scale adoption. This has led to a major rethink by researchers and partners of the methodology and approach taken and the types of research conducted in the project.

Conclusions

Whilst technologies exist that increase soil productivity and are profitable for farmers there are many other factors preventing them from adopting the technology. Fallowing the land for example, is not possible where small land sizes or high population densities exist and where seed supply for these legume cover crops is not good. In eastern Uganda, where the population pressure is much lower and where natural fallowing is still part of the farming system, the opportunities for improved fallowing or biomass transfer is much higher. Even so, issues of increased labour requirements for incorporation or collection of biomass are commonly cited by farmers during evaluations.

In this dynamic environment farmers assess the different management options available to them and adapt them to fit their own circumstances and production objectives. For example, growing Tithonia on-farm in available niches (around the field boundaries, for example) is one way of over-coming shortage of Tithonia and reducing the labour that would be needed if collecting the biomass from off-farm locations. Innovations in using these legume cover crop and biomass transfer species are very common. This work has identified many adaptations/innovations by farmers not just for increasing crop production but also for pest and weed control, consumption of the seeds and for livestock feeding.

The criteria used for species selection and the farmers' innovations provide essential feedback to the participatory action research approach as they reflect the opportunities and constraints of the production systems of the farmers and raise many new areas of research, opportunities of evaluation of new technologies and species and the better targeting of existing information.

References

Adamo A.K. (2001). Participatory agricultural research processes in eastern and central Ethiopia: Using farmers' social networks as entry points. CIAT Occasional Publications series, No. 33. CIAT, Cali, Colombia.

Bellon, M.R. (2001) Evaluation of current and new technological options. In: Participatory research methods for technology evaluation: A manual for scientists working with farmers. pp49-72. CIMMYT, Mexico

Braun, A. (2001). Linking logistics II: Exploring linkages between farmer participatory research and computer based simulation modelling. 15-20 October 2001, ICRISAT Bulawayo, Zimbabwe. CD-Rom ISBN 0-743-08290-X

Buresh, R.J. and Niang, A.I. (1997) Tithonia diversifolia as a green manure: awareness, expectations and realities. Agroforestry Forum 8(3): 29-31

Delve R.J. and Jama B. (2002a). Developing organic resource management options with Farmers in Eastern Uganda. Paper presented at the 17th World Congress of Soil Science, Bangkok, Thailand, 14-22nd August 2002

Delve, R.J. and Jama, B. (2002b) *Mucuna pruriens* and *Canavalia ensiformis* legume cover crops: Sole crop productivity, nutrient balance, farmer evaluation and management implications. Submitted to Biology and Fertility of Soils

Douthwaite, B., Delve, R.J., Ekboir, J. and Twomlow, S. (2002) Contending with Complexity: The Role of Evaluation in successful INRM. Paper presented at the CGIAR INRM Workshop, 16-19 September, 2002, ICARDA, Aleppo, Syria

Drechsel, P., Steiner, K.G., Hagedorn, F. (1996). A review on the potential of improved fallows and green manure in Rwanda. Agroforestry Systems 33 109-136

Ecoregional Alliance. (2001). Clean and green food production for a healthier, more prosperous future. Printed in India by Pragat Offset Pvt. Ltd

Giller, K. E., Cadisch, G., Ehaliotis, C., Adams, E., Sakala, W. D., Mafongoya, P. L. (1997). Building soil nitrogen capital in Africa. In: R. J. Buresh, R., Sanchez, P. and Calhoun, F (eds.) Replenishing soil fertility in Africa. SSSA Spec. Publ. 51. SSA, Madison, WI, USA pp. 151-192

Hernandez-Romero, L.A. (2000). Logistic preference ranking analysis for evaluating technology options. A user manual. CIAT Publication No. 319.IPRA-CIAT Proyect.

Marra, M., Pannell, D.J and Abadi Ghadim, A. (2002). The economics of risky, uncertainty and learning in the adoption of new technologies: Where are we on the learning curve? Agricultural Systems, (In press).

Miiro, R., Kabuye, F., Kiguli, D., Mukaaya S. (2002). Baseline survey of farming systems and soil management in Tororo district. Africa2000 Working Document

Obonyo, O. C. (2001). The adoption of biomass transfer technology in western Kenya. MSc. Thesis. Kwame Nkurumah University of Science and Technology, Kumasi, Ghana.

Onesimus, S. (1999). Needs and assessment for agricultural research in the Mount Elgon Hill sides farming systems.

Sanchez, P.A., Shepard, K.D., Soule, M.J., Place, F.M., Buresh, R.J., Izzac, A.N., Mokwunye, A.U., Kwesiga, F.R., Ndiritu, C.G. and Woomer, P.L. (1997). Soil Fertility Replenishment in Africa: An investment in natural resource capital, In: R. J. Buresh, R., Sanchez, P. and Calhoun, F (eds.) Replenishing soil fertility in Africa. SSSA Spec. Publ. 51. SSA, Madison, WI, USA

Smaling, E. M. A., Nandwa, S. M., Janssen, B. H. Soil fertility in Africa is at stake. In: R. J. Buresh, R., Sanchez, P. and Calhoun, F (eds.) Replenishing soil fertility in Africa. SSSA Spec. Publ. 51. SSA, Madison, WI, USA pp. 151-192

Rommelse, R. (2001). Economic assessment of biomass transfer and improved fallow trials in Western Kenya. ICRAF Working Document

Tumuhairwe, J.B., Jama, Delve, R and Rwakaikara-Silver, M.C. (2002). Mineral nitrogen contribution of *Crotalaria grahamiana* and *Mucuna pruriens* short fallow in eastern Uganda. Submitted to Plant and Soil

Tumuhairwe, J.B., Jama, Delve, R and Rwakaikara-Silver, M.C. (2002). Financial benefits of *Crotalaria grahamiana* and *Mucuna pruriens* short-duration fallow in eastern Uganda. Submitted to Journal of Agricultural Economics

Table 1. Farmers' assessment of the LCCs and BT species

LCC/shrub	Positive aspects	Negative aspects
Mucuna pruriens Local name: none	Improves soil fertility Suppress weeds effectively Produce high biomass Quick maturing	x Not edible x Not good for intercropping (Climbs the crops) x Requires high labour for clearing and incorporation x Can harbour snakes and wild cats if planted near the home
Canavalia ensiformis Local name: Yathipendi (medicine for banana) or Akengu ka angu (trap for the hyena)	Improves soil fertility Has fodder value Suppresses weeds Easy to multiply (high seed production) Good for intercropping	x Not edible
Crotalaria grahamiana: Local name: none	Improve soil fertility Suppress weeds	x Has pest problem – scaring caterpillars
Tephrosia vogellii Local name: Yathi fuuko (medicine for mole rat) or Yathirechi (medicine for fish)	Improves soil fertility Control mole rat	x Has pest problem that eats the pod, hence poor seed formation
Labalab Local name: none	Improves soil fertility Has fodder value Suppresses weeds	X difficult to obtain seed
Tithonia diversifolia Local name: Mawuwa	Improves soil fertility Medicine for malaria & stomach aches Has pesticidal properties Fodder for goats	x It is a weed

Table 2. Criteria developed by farmers for ranking of the LCCs and biomass transfer species

Criteria	Justification of criterion
Yield increase of crop after fallow or intercrop	- Weight of grain, bunch, fruit etc
Crop vigour of crop after fallow or intercrop	- Health - Greenness of leaves
Soil fertility increase	- Change of soil colour to dark - Depth of soil increased - Ease of ploughing - Soil erosion control - Moisture retention - Time taken to cause significant fertility increase
Ease of germination, establishment & seed production of the LLC or shrub	- More seed produced in a short time & viable for a longer time. - Small seed difficult to collect
Multiple uses of the LLC or shrub	- The number of other additional uses from the LCC or shrub e.g. firewood, medicine, fodder etc.
Suitability for intercropping	- Intercrop compatibility i.e. minimal competition of the LCC or shrub with the crop
Ability to control weeds	- Dense canopy formation which suppress undergrowth
Amount of biomass production	- Number of leaves - Size of leaves - Ground coverage - Shorter maturity period
Labour requirement for clearing, uprooting, cutting and incorporation	- Ease of bush clearing, uprooting, cutting stems and leaves & then incorporation into the soil

Table 3. Overall raking of the LCCs and biomass transfer species by the groups

Group name	Ranking of species					
	Mucuna	**Canavalia**	**Lablab**	**Crotalaria**	**Tephrosia**	**Tithonia**
Manakori	1	2	5	6	4	3
Katamata	2	3	4	1	6	5
Umoja	1	2	6	2	4	4
Boke A	1	2	5	3	5	4
Boke B	1	2	6	3	5	4
Aputiri	2	5	4	3	6	1
Amorio	2	3	5	6	4	1
Osukuru post test club	2	4	6	1	3	5
Anyari Nglechom	5	4	6	3	2	1
Jachandi	1	3	6	4	5	2
Chemo Apecho	2	3	5	1	6	4
Chandere	1	2	6	3	4	4
Tekere	1	2	4	3	6	5
Geno	4	5	3	2	6	1
Abongit Chymeromo	1	2	6	3	5	4
Theketheke	1	3	5	4	6	2
Mari	1	3	6	4	5	2
Temokinyieko	1	2	6	3	5	4
Ichi Awati	1	3	6	2	5	4
Total	31	55	100	57	92	60
Rank order	1	2	6	3	5	4
1 = most preferred species 6 = least preferred species						

Table 4. Distribution of acceptance frequencies

Species	Ranking order										
	1	2	3	4	5	6	7	8	9	10	Total
Mucuna	7	5	0	1	0	0	0	1	0	0	14
Canavalia	0	5	4	1	1	2	0	0	0	0	13
Lablab	0	0	1	2	3	2	3	2	1	0	14
Crotalaria	3	2	5	0	2	1	1	0	0	0	14
Tephrosia	0	1	0	1	4	5	2	1	0	0	14
Tithonia	4	0	1	3	4	1	1	0	0	0	14
Total											134

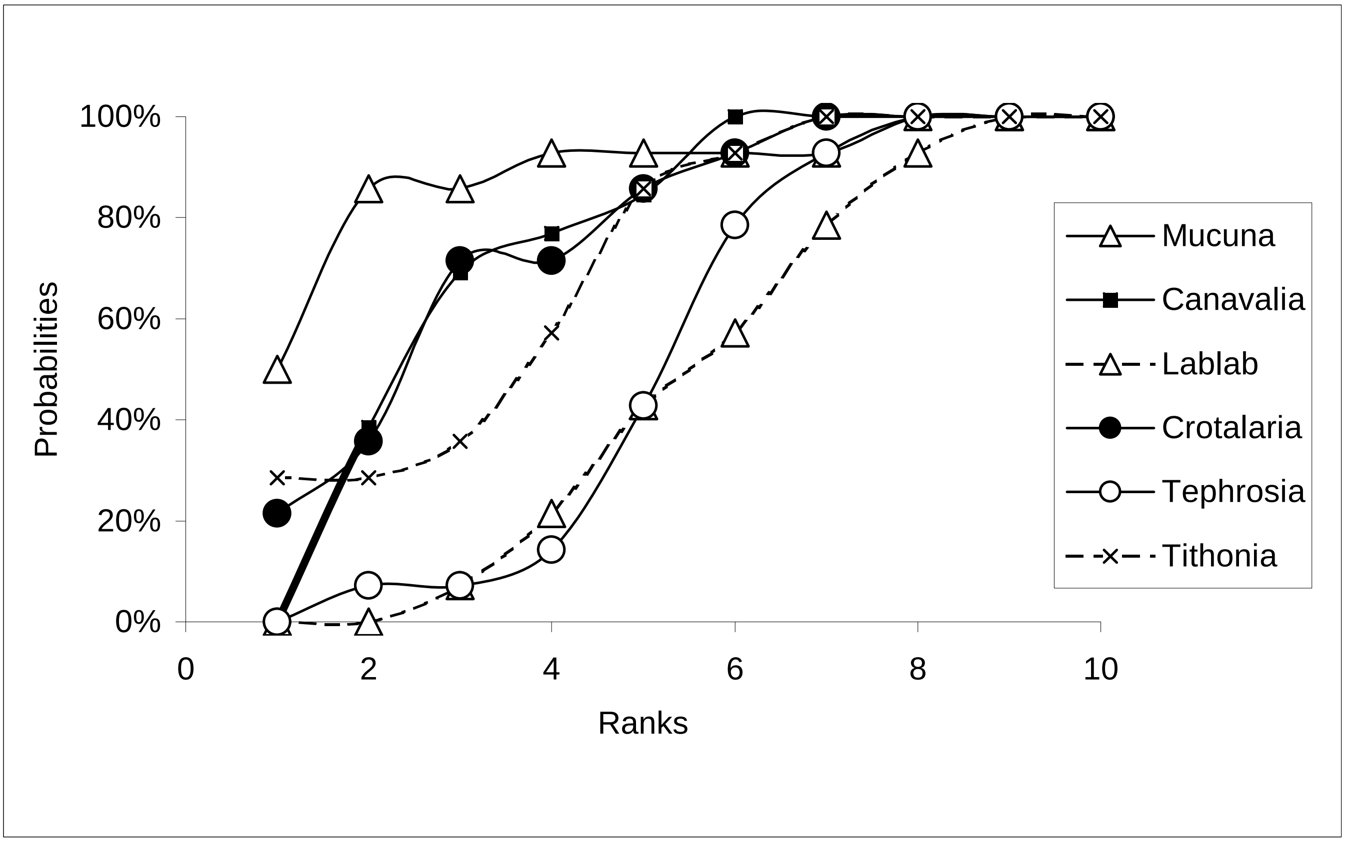
Table 5. Statistical analysis of the logistic regression

Technology	Estimated parameter b (intercept)	Parameters m (slope)	Standard error (SEb)	Wald Chi-Square	Chi Square	Significance (P<0.15)
Mucuna	0.69	0.04	0.07	10.08	0.00	** Differs statistically
Canavalia	0.25	0.10	0.13	1.96	0.16	Does no differ
Lablab	-0.24	0.13	0.06	4.20	0.04	** Differs statistically
Crotalaria	0.31	0.08	0.09	3.46	0.06	** Differs statistically
Tephrosia	-0.22	0.14	0.10	2.24	0.13	** Differs statistically
Tithonia	0.20	0.10	0.09	2.24	0.13	** Differs statistically

Table 6. Farmer innovations with the legume cover crop technologies

LCC/BT species	Research recommended management and use	Modification in management and use
Crotalaria	Intercrop with maize or as a one season fallow crop. When mature, uproot and mulch in maize, beans, sorghum, millet, cotton, etc. Thresh pods to get seed. Mulch	Boundary planting around the homesteads Intercrop with beans to control nematodes and other bean diseases. Seed put together with bean seed during storage controls bean storage pests
Mucuna	Use it as a one season fallow crop, uproot at planting and mulch in the following crop Use as cover crop in banana plantations	Attempts to cook it and eat the seed as sauce Efforts to crash seed to make animal feed Good feed for goats, cattle and rabbits
Canavalia	Canavalia intercropped with coffee, maize and bananas	Used to scare off hyenas in the olden days (and monkeys these days)
Lablab	Grow for two seasons as a fallow crop, uproot at planting and mulch in the following crop. Use as a fodder crop and as cover crop in banana plantations Livestock feed	Seed and the leafy vegetation edible (i.e. used as sauce)
Tephrosia	Plant around field for trapping the mole rat Plant as a sole crop	Leaves are crashed, poured into rivers and streams to catch fish Doubt on its effectiveness in controlling the mole rat
Tithonia	Boundary planting, biomass Transfer	Leaves used for treatment of stomach ailments and fevers Planting from cuttings rather than from seed

Figure 1: Comparison of acceptance of technologies



Draft paper

Evaluation of cowpea and Lablab dual-purpose legumes

R. Delve and P. Nyende
TSBF-CIAT, PO Box 6247, Kampala, Uganda

Rationale: The criteria used for legume cover crop (LCC) species selection and the farmers' innovations with these LCC species in the participatory action research of INSPIRE in Tororo district revealed new constraints and opportunities of the farming system. Farmers' assessment of the LCCs revealed many positive and negative aspects for each species, but of major concern was on Mucuna and Canavalia which were disliked because their seeds are not edible yet they looked very attractive to eat, and are produced in large numbers, even in dry seasons. Despite the strong caution not to eat the seeds, a few farmers attempted to cook and eat seeds from these LCC seeds. A research agenda that address this new challenge of proving dual-purpose legumes was introduced in 2002. Two species cowpea and lablab were evaluated as dual-purpose legumes to address farmers' prioritized need for food, fodder and soil fertility improvement

Evaluation of dual purpose cowpea: Cowpea International Trial 101
Fifteen elite lines of cowpea identified and developed by the Grain Improvement Program of IITA, Nigeria, were introduced with two main objectives of the trials:

1. To evaluate the performance and farmer evaluations of these lines in view of selecting the most promising as regards to improving soil fertility and provision of food and fodder.
2. To provide grain legumes improvement programs with regional evaluation data and to select lines for further testing

Methodology: 15 cowpea lines (including a local check) were tested on-station at the Distinct Agricultural Training and Information Centre in Tororo, eastern Uganda. Crop management, trial layout and data collection was strictly followed based on recommendations from the Grain Improvement Program of the IITA. In addition, a farmer evaluation of the varieties was also done at grain harvesting stage with the objective of evaluating the varieties for acceptability and seed multiplication. This was done on a farmer field day organized in collaboration with Africa 2000 Network and the DATIC management. In a participatory manner, 20 farmers from each of the two sub counties of Kisoko and Osukuru participated in an absolute evaluation of the 15 varieties.

Results: Before a field a valuation farmers were engaged in a discussion on several aspects of the cowpea crop. Farmers revealed that they grow only one variety of cowpea, locally known as 'Ngori'. This has either white or brown seeds. The following were listed as main ways in which the crop is utilized:

- Leaves (at 3-4 WAP) are boiled and eaten as sauce (vegetable) with other foods
- Seeds are roasted and eaten as snack e.g. with tea
- Seeds are boiled and made into samosas using baking flour
- A meal composed of cowpea serves as a food reserve during travels and is eaten while travelling as keeps long in the stomach
- Cowpea is used in exchange for labour if there is no cash available at hand
- Cowpea is also known to improve soil fertility

Cowpea is mainly planted during the short rain season because it does not tolerate too much rain. Farmers traditionally broadcast cowpea and ensure larger spacing compared to that recommended by the Grain Improvement Program of IITA (20cm x 50cm). Leaves are picked at 2-3 weeks after planting and used as vegetables. Also at this time thinning is done and leaves and/or whole stems are used in sauce preparation. Pruning encourages more branches to sprout and more flowers to develop and hence more yields. Young and tender leaves are continuously picked during the entire growing period for sauce. In Tororo, there are several grain legume food crops grown but the major ones in order of importance are cowpea, groundnuts, common bean, simsim, soyabean and green gram. Cowpea was ranked first because it fetches more income than other grains grown in the area.

Farmers' criteria used to evaluate the cowpea varieties

The following criteria was consensually agreed upon and enlisted by the farmers and used to conduct an absolute evaluation:

- Multiple utilization (e.g. as vegetable sauce, Sumbusa)
- Pest and disease tolerance
- Improve soil fertility
- Good taste and satisfaction obtained when eaten (i.e. ability to stay in the stomach for long)
- Grain yield obtained (i.e. many grain filled pods)
- Marketability of the grain seed (i.e. big seed, uniform colour)

This present season the farmers are further evaluating the five most promising varieties. In addition, two more varieties breed by Makerere University are being evaluated alongside these. Evaluations will be done at two stages, at 2-3 WAP (for vegetable attributes) and at harvest maturity for grain and biomass yield.

The evaluation was done by men and women separately to cater for gender differences.

Table 1. Women's ranking of cowpea lines

Farmer ranking	Replicate No.			
	REP 1	REP 2	REP 3	REP 4
1	IT95K-238-3	IT98K-205-8	Local check	IT95K-238-3
2	Local check	IT95K-238-3	IT98K-205-8	Local check
3	IT94K-437-1	IT97K-499-38	IT94K-437-1	IT98K-205-8
4	IT98K-279-3	IT94K-437-1	IT95K-238-3	1T98-279-3
5	IT98K-205-8	Local check	1T98D-1399	IT98K-1382
6	IT98K-1382	IT97K-350-4-1	IT98K-279-3	IT98K-1382
7	IT95K-463-6	IT98K-463-6	IT98K-1312	IT97K-499-34
8	IT97K-350-4-1	IT97K-1068-7	IT97K-566-6	IT98K-131-2
9	IT97K-1068-7	IT97K-449-38	IT97K-350-4-1	IT97-556-4
10	IT97K-499-38	IT97K-350-4-1	IT94K-440-3	IT97K-1068-7
11	IT97K-499-39	IT98K-131-2	IT97-499-8	IT94K-440-3
12	IT94K-440-3	IT97K-1069-7	IT94K-440-3	IT98K-463-6
13	IT98K-131-2	IT94K-440-3	IT94K-437-1	IT94K-440-3
14	IT97K-556-4	IT98K-1382	IT98K-463-6	IT97K-350-4-1
15	IT98D-1399	IT98D-1399	IT98K-1382	IT98D-1399

Table 2. Men's ranking of cowpea lines

Farmer ranking	Replicate No.			
	REP1	REP 2	REP 3	REP 4
1	Local check	IT98K-205-8	Local check	Local check
2	IT98K-205-8	IT97K-499-38	IT95K-238-3	IT95K-238-3
3	IT98K-279-3	IT94K-437-1	IT94K-437-1	IT98K-205-8
4	IT98D-1399	IT95K-238-3	IT98K-279-3	IT98K-278-3
5	IT97K-1068-7	Local check	IT98K-205-8	IT97K-1068-7
6	IT95K-238-3-3	IT94K-440-3	IT98K-1382	IT97K-279-3
7	IT97K-499-38	IT97K-350-4-1	IT97K 350-4-1	IT98K 1382
8	IT94K-437-1	IT97K-556-4	IT98D-1399	IT97K 556-4
9	IT94K-446-3	IT98K-279-3	IT97K-1068-7	IT97K-350-4-1
10		IT97-1068-7	IT97K-1068-7	IT98D-1399
11	IT97K-350-4-1	IT97K-499-39	IT97K-499-39	IT97K-499-39
12	IT98K-1382	IT98K-463-6	IT97K-556-4	IT94K-437-1
13	IT97K-499-39	IT98K-1382	IT94K-440-3	IT98K-131-2
14	IT97K-556-4	IT98K-131-2	IT98K-131-2	IT94K-440-3
15	IT98K-463-6	IT98D-1399	IT98K-463-6	IT98K-463-6

The central objective in conducting a genderized evaluation of the cowpea lines was to make proactive efforts to ensure that women participate and benefit from the technology and capture their innovations. It was anticipated that women face different constraints from men and have different incentives to invest in or adopt cow pea varieties. Based on the evaluation results and field observations, men gave higher score to the local variety compared to the women. However, with regard to the new varieties under evaluation, there wasn't much difference in preference between women and men as reflected also in the evaluation criteria. Furthermore, based on the criteria enlisted by the farmers, the following varieties look promising: IT98K-238-3-3, IT98K-279-3, IT98K-205-8, IT98K-279-3, IT95K-238-3.

Evaluation of dual-purpose lablab: Accessions from CSIRO-Australia

One of the major problems identified by farmers during participatory research was the lack of seed production from Lablab species due to late flowering and flower abortion, that was severely inhibiting adoption of an otherwise preferred dual-purpose legume option. Thirty-three lines from CSIRO that had early flowering characteristics were introduced with two main objectives of the trials:

1. To evaluate the performance of these lines in view of selecting the most promising as regards to improving soil fertility and provision of food
2. To provide grain legumes improvement program with an opportunity to select lines for further testing and use, either directly as varieties or as source of breeding materials.

Methodology: In the 2002b season an on-station evaluation was established at Kawanda Agricultural Research Institute, Kampala, Uganda to evaluate the different accessions for a range of phenotypic characteristics and biomass production. Results from this work are not presently available

African Crop Science Journal (submitted)

Mineral nitrogen contribution of Crotalaria grahamiana and Mucuna pruriens short-term fallows in eastern Uganda

Tumuhairwe, J.B[1]., B. Jama[2*], and R. Delve[3] , M.C. Rwakaikara-Silver[1]
[1]Makerere University, Department of Soil Science, P. O. Box 7062, Kampala, Uganda
[2]International Centre for Research in Agroforestry, P. O. Box 30677, Nairobi, Kenya.
[3]Tropical Soil Biology and Fertility (TSBF) and International Centre for Tropical Agriculture (CIAT), P. O. Box 6247, Kampala, Uganda

Abstract:
Nitrogen (N) is one of the major limiting nutrients to crop production in Uganda and is depleted at faster rates that replaced. Consequently, yields at farm level are less than 30% of the expected potential. Paradoxically, the majority subsistence farmers are poor to afford use of mineral fertilisers but improved fallow have been reported economically feasible in such conditions. Therefore, a study was initiated in Tororo district, eastern Uganda (i) to determine mineral N contribution of *C. grahamiana* and *M. pruriens* short-duration fallows compared with farmers' practices of natural fallow, compost manuring and continuous cropping, (ii) sampling period that closely related to maize grain yield was also determined and also (iii) whether improved fallow provided adequate mineral N for optimum grain yield compared to farmers' practices. It was noted that improved fallows increased mineral N at Dina's site during fallowing (at 0 week sampling), and in the first and fifth week after incorporating their biomass than farmers' practices. For instance, at harvesting fallows (0 week sampling), *C. grahamiana* and *M. pruriens* had 12.68 and 12.97 mg Kg^{-1} N compared to 6.79 and 7.79 mg kg^{-1} N from following natural fallow and continuous cropping respectively. However, no significant increase was realised at Geoffrey's site at any of the sampling dates attributed to low biomass yield and incorporated. *C. grahamiana* increased grain yield by 29.3% (Dina's site) and 56.6% (Geoffrey's site) and *M. pruriens* by 36.0% (Dina's site) and 27.2% (Geoffrey's site) compared to natural fallow with -11.9% (Dina's site) and 17.4% (Geoffrey's site) then compost manure -9.6% (Dina's site and 0% (Geoffrey's site) in relation to continuous cropping as a bench mark. Supplementing the land use systems LUS (*C. grahamiana*, *M. pruriens*, natural fallows, compost manure and continuous cropping) with inorganic N fertiliser as urea significantly increased grain yield in all except *C. grahamiana* at both sites. There were two peaks on mineral N. The first and major peak occurred in the third week dominated by NO_3^--N and the minor one in the tenth week with NH_4^+-N prominent consistent at both sites. Mineral N in the fifth week after incorporating biomass was most closely related to grain yield followed by sampling at planting (0 week).

The second Masters thesis (Comparison of the effects of *Mucuna pruriens, lablab purpureus, canavalia ensiformis* and *crotalaria grahamiana* on soil productivity in Tororo district eastern Uganda) was submitted in September 2002, the abstract form this thesis is reproduced here.

Masters thesis submitted in September 2002

The effect of green manures, Mucuna, Lablab, Canavalia and Crotalaria on soil fertility and productivity in Tororo District, Uganda.

Matthew Kuule
Makerere University, Kampala, Uganda

Abstract
There is much concern over the declining crop yields over much of sub-Saharan Africa, and has largely been blamed on declining soil fertility, since increasing population has rendered traditional shifting cultivation and long-term fallowing, less practical. Strategies such as mineral fertilizer application, use of manure (compost and animal) and green manuring have been shown to sustain and/or increase soil productivity. Mineral fertilizers restore lost or limited soil nutrients fast, but are expensive for most farmers and do not improve soil organic matter. Similarly, compost and animal manure use is limited by the quality of the composted and/or feed material as well as the labour requirements for their preparation and application to farm fields. Legume cover crops, which are produced on the field with the crops and later incorporated into the soil to provide plant nutrients upon decomposition, could be a viable option for soil productivity improvement, especially in smallholder low-input agriculture systems. Whereas the technology has been widely adopted in the tropics, it is still low in Uganda, probably due to lack of awareness and performance data. This study was therefore planned to demonstrate the value of legume cover crops on soil productivity improvement and to determine and compare the economic viability of four legume species (*Mucuna pruriens, Crotalaria grahamiana, Lablab purpureus* and *Canavalia ensiformis*) in order to give sound recommendation for wider adoption of the technology. To be of relevance to farmers, six on-farm trials (each farmer as a replicate) were set up in two sub-counties Kisoko and Osukuru, and another on-station trial at the District Agricultural Training Centre (DATIC) with four replicates, in Tororo District, eastern Uganda. In August 2000, maize (cv. Longe1) was established on five-5 x 5 m plots and at first weeding stage (4WAP), the four legume cover species were each planted between maize rows in all the plots except the control (maize monocrop). After harvesting maize in December 2000, the cover crops continued to accumulate biomass for two more months, and in February 2001, the above ground biomass of the cover crops and of weeds was harvested, fresh weight taken, sampled for drymatter determination and incorporated into the soil during land preparation for the long rain season in March 2001. Production costs that were different for different treatments were estimated and recorded during the experiment. Maize yields were also recorded to allow computation of the returns from legume cover crops using marginal rate of return of non dominated treatments, as a basis for recommending the cover crop species to farmers. Results indicated significant ($p<0.05$) maize yield increases for Crotalaria and Lablab treatment of 96.4% and 69.6 % respectively on farmers' fields in the second season (after legume biomass incorporation) and non-significant yield response to all legume cover crops on-station in both seasons, were obtained. The significant maize yield response to Crotalaria and Lablab on-farm and not on-station was probably due better synchrony of nutrients released from their biomass on an initially poorer soil at the on-farm compared the relatively better soil on-station. The analysis of costs and benefits revealed favourable marginal rates of return to Crotalaria, Canavalia and Mucuna of 246, 120 and 30.4% respectively and were all recommended for adoption with more emphasis on Crotalaria.

Draft paper to be submitted to Journal of Agricultural Economics or African Crop Science Journal

Financial benefits of Crotalaria grahamiana and Mucuna pruriens short-duration fallow in eastern Uganda

Tumuhairwe, J.B[1]., B. Jama[2], and R. Delve[3], M.C. Rwakaikara-Silver[1]*
[1]Makerere University, Department of Soil Science, P. O. Box 7062, Kampala, Uganda
[2]International Centre for Research in Agroforestry, P. O. Box 30677, Nairobi, Kenya
[3]Tropical Soil Biology and Fertility (TSBF) and International Centre for Tropical Agriculture (CIAT), P. O. Box 6247, Kampala, Uganda

Abstract

Crotalaria grahamiana and *Mucuna pruriens* improved fallows are gaining popularity among smallholder farmers in Uganda to address soil fertility decline. The technology supplies nutrients and increases crop yields but its economic viability is uncertain in eastern Uganda. Therefore, two researcher-managed experiments were established in Tororo District, eastern Uganda to determine the financial benefits of the *C. grahamiana* and *M. pruriens* improved fallow compared to farmers' practices of natural fallow, compost manure and continuous cropping. Higher returns to land were obtained from improved fallow compared to farmers' practices. *C. grahamiana* realised US$267.4 (Dina's site) and $ 283.2 (Geoffrey's site), and *M. pruriens* had $284.1 (Dina's site) and $248.7 (Geoffrey's site) compared to natural fallow $223.3 (Dina's site) and $274.3 (Geoffrey's site), compost manure $70.9 (Dina's site and 114.2 (Geoffrey's site) and continuous cropping $314.2 (Dina's site) and $314.2 (Geoffrey's site) per hectare. Improved fallows saved on labour compared with continuous cropping and compost manure except for natural vegetation fallow. Higher returns to labour were obtained through use of improved fallow than compost manure and continuous cropping. Returns to labour of \$0.54 day^{-1} were obtained for compost manure (at Dina's site), which is less that the wage rate at \$0.57 day^{-1} indicating a loss in labour invested.

The second Masters thesis (An assessment of the profitability and acceptance of alternative soil improvement practices in Tororo district, Uganda) was submitted in September 2002, the abstract form of this thesis is reproduced here.

Agricultural production in Eastern Uganda is declining due to increasing population pressure on the land. A resultant feature is the dependence of soils on external inputs to attain acceptable crop yields. Resource-poor smallholder farmers, who form the majority of the farmer population in this area, can typically ill-afford recommended levels of inorganic fertilizer use to replenish lost nutrients. Alternative options to expensive and often unavailable inorganic fertilizer use for this small scale farmer population include the integrated use of inorganic fertilizer and organic inputs such as legume cover crops and biomass production shrub and tree technologies. These technologies were incorporated into the farming systems in Eastern Uganda, Tororo district, in 1998 through farmer groups. An economic evaluation of 10 researcher-designed-farmer managed maize trials using *Mucuna pruriens* and *Canavalia ensiformis* fallow and *Tithonia diversifolia* biomass land use systems were conducted. The profitability was determined using gross margins, after which modelling produced the optimal land use system. A survey of 108 respondents was also conducted to determine the acceptance and farmer-perception of 8 previously exposed shrub and tree species. The economic evaluation favoured the use of Integrated Nutrient Management of soil amendments. The 100% incorporation of Mucuna produced the highest benefits of 185,641/= ha^{-1} as opposed to the net benefit of 134,901/= that would be produced in the optimal solution from 0.6 ha using 191 labour days. The application of 0.91t ha^{-1} + N biomass system would produce the highest benefits of 445,744/= ha^{-1} with an optimal net benefit solution of 342,080/= on 0.8ha using 263 labour days. The survey results showed that in the sample size, the acceptance rate was 53 percent. The age and area under shrub were significantly different (0.01) across accepters and non-accepters. The cultivated area (0.1) and employment activities (0.05), institutional support such as belonging to groups and number of extension visits significantly also differed. Alternative uses of shrubs and trees, use of other complimenting inputs and perceptions of the soil fertility were highly significant across acceptor category. Farming experience and use of farmyard manure were not significant. *Sesbania sesban,* and *Mucuna pruriens* were found to be the most popular shrubs (36.69%, and 20.6% respectively) and problematic (36.22%, and 25.20% respectively). Popular uses were weed suppressant uses (17.5%) and fuel wood production (23%) for 7 out of 8 shrubs. Major reported problems were the increased labour demands, (21.5%), pest and vermin association (25.3%), and access to planting material and seed (26.7%). Further economic studies that will determine the optimal levels at which the incorporation of livestock management systems into the cropping systems using integrated nutrient management options are recommended. Farmer designed-farmer managed trials would establish preferred farmer management practices to ensure sustainability of these land use systems.

Synthesis paper presented at regional workshop

Impacts of land management options in western Kenya and eastern Uganda

Delve[1], R. J. and Ramisch[2], J. J.
[1] Tropical Soil Biology and Fertility Institute of International Centre of Tropical Agriculture (TSBF-CIAT), PO Box 6247, Kampala, Uganda; email: r.delve@cgiar.org
[2] TSBF-CIAT, PO Box 30592, Nairobi, Kenya, email: j.ramisch@cgiar.org

Introduction

Over the last 10 years the image of agricultural and environmental crises in sub-Saharan Africa (SSA) has become increasingly common. Soil erosion and soil fertility loss are considered to be undermining the productive capacity of the agricultural systems (Giller *et al.*, 1997; Sanchez et al., 1997; Smaling *et al.*, 1997). These problems have been ascribed to many different causes, social, economic, biological and physical. Many authors have also highlighted concern over the increasing land degradation in the highlands of East Africa (e.g. Hilhorst and Muchena, 2000; Farley, 1995; Getahun, 1991) where increases in agricultural production in recent decades have been achieved through intensification of existing agricultural practices and through expanding the cultivated areas of land, especially in fragile environments. Soil degradation, soil erosion and loss of soil fertility have been widely quoted as resulting from these intensive and extensive agricultural production systems.

Blaming smallholder farmers for this degradation is over simplistic in the least. Furthermore, tropical agricultural production systems are characterized by dynamic features, resilience and many examples of modified production practices to cope with and adjust to changes (Brookfield and Padoch, 1995; Farley, 1995; Goldman, 1995). Smallholder farmers use a wide range of resource management practices and production strategies specific to their agro-ecology to minimise risk, cope with change and shocks and to manage the environment (ecological, social, economic etc) they operate within. These can include, for example, agricultural intensification, expanded market-orientation, increased capital and labour investment. Alternatively, farmers have been found to exploit their resource base where constraints are too high, the returns to investment are too low (even negative, as when staple commodity prices plummet during bumper harvests), or environmental conditions too erratically variable for secure investment. Where purchased inputs or labour are scarce, mining the soil's nutrient capital resource can appear to smallholders as good economics and an acceptable cost of agricultural production.

This paper uses evidence from two sites in eastern Uganda and western Kenya to investigate land management, land use changes, and the policy environment within which smallholders have to operate, and assess their impacts on smallholder farmers' production strategies. Both sides of the border have similar agro-ecosystems and cropping systems, with eastern Uganda through to western Kenya occupying a gradient with changing soil types, from the alfisols in Uganda to humic nitisols in western Kenya, increasing agricultural production and also increasing population densities from east to west. This has resulted in a range of land use systems to manage this gradient.

Land management technologies

Ugandan and Kenyan national research institutions (in collaboration with international agricultural research centres) have developed an array of technologies that can effectively address local production problems, for example, improved banana and maize varieties for various agro-ecological zones, as well as, legumes and cover crops that improve soil fertility and provide fodder. Many of these technologies have, however, not been disseminated adequately to farmers and have, therefore, little impact at the farm level. The need for improved dissemination of knowledge to farmers has been identified by many studies (e.g. Onesimus *et al.*, 1999). To do this, it is increasingly being recognised that the best approach is one in which farmers, the local administration, and the community participate actively.

Examples of technologies developed in the region by collaborative research between farmers and scientists include:

Phosphorus replenishment. Phosphorus is a major limiting nutrient to much of the region's crop production due to low soil P availability and many soils' high P-fixing capacity, especially in western Kenya. The socio-economics of smallholder production limit the feasibility of using fertilisers, but combining organic residues with locally available, low-cost rock P, can improve P availability to crops. As well, research on a P-fixing Nitisol in western Kenya has shown that soil P replenishment using seasonal additions of small rates of P fertilisers could be attractive to some small-scale farming systems (Nziguheba, 2001). Seasonal additions of 25 kg P ha^{-1} increased maize yield with gradual replenishment of soil P. Smaller rates of 10 kg P ha^{-1} contributed to soil P depletion, while large seasonal applications of 150 kg P ha^{-1} resulted in low efficiency of applied fertilisers.

- *Legume cover crops*. In regions where natural fallowing is still practiced (as in Eastern Uganda), green manure species like *Mucuna pruriens* and *Canavalia ensiformis* increases the following maize yields (Delve and Jama, 2002a). In addition, the significant increases in associated maize stover production increased options available to farmers, such as using it for livestock feed or bedding, soil erosion control, compost making, or mulching the banana crop. Delve and Jama (2002a) also found that incorporating 50% or 100% of the *in-situ* produced biomass did not result in significantly different increases in maize grain and stover yield. This would allow farmers to use 50% for incorporation and the remaining 50% for livestock feed, sale to other farmers, or to produce hay for dry season feed. Increasing the resource management options and therefore the production options of the farming enterprise is critical where land sizes and the area available for non-food crop production are small, and where cash is not readily available to buy inputs for crop and livestock production.
- *Biomass transfer*. In both western Kenya and eastern Uganda application of high quality local materials, such as *Tithonia diversifolia*, has shown good potential to increase productivity. Work in western Kenya, supplying a constant rate of 15 kg P ha^{-1} through combinations of Tithonia leaves low-quality maize stover and triple super-phosphate (TSP), showed that maize yields increased between 18-24% as the share of P contributed by Tithonia in the residue–fertiliser mix was increased above 36%. The results indicate that a high quality organic input can be more profitable than using inorganic P, and comparable to or more effective than inorganic P in increasing P availability in the soil. Work in Uganda combining Tithonia with fertilisers also obtained the greatest benefits by maximising the proportion of Tithonia in the mixture (Delve and Jama, 2002b).

Whilst technologies exist that increase soil productivity and are profitable for farmers there are many factors limiting technology adoption. The fact that food production is the key priority of the farmer means that they are very risk averse and need to produce a food crop every season. Even where land is not apparently scarce, investing present resources in the possibility of future increased production is not necessarily attractive to farmers. As a research farmer in Kenya commented, '*Its better to have even one gorogoro tin of maize [from a depleted field that was planted with maize] than to be guaranteed no maize at all this season by planting a cover crop we can't eat*'. Issues of increased labour requirements for incorporation or collection of biomass are also commonly cited by farmers during evaluations of the organic technologies. In western Kenya there are even examples of teachers using 'free' labour of children coming to school to harvest Tithonia for use on school plots.

The implicit assumption of most agricultural research is that farmers' current resource management decisions are not the optimal ones, and that providing them with 'better information' would lead them to better choices. However, without understanding farmers' priorities and constraints the rationality of their current decisions will also be misunderstood. Similarly, by ignoring farmers' existing knowledge (or not accurately locating the gaps in that knowledge) the impacts of improved land management technologies will be minimal. Agricultural knowledge, access to new sources of information, and control of resources can vary considerably within a given community, especially across axes of difference such as gender or age. Technologies that are designed collaboratively by researchers, extensionists, and farmers are more likely to correctly target the socio-economic and agro-ecological niches where they will be most relevant.

Adaptations by farmers

Innovations in using these soil fertility management technologies are very common. A recent survey identified many adaptations/innovations by farmers using cover crop and biomass transfer species not just for increasing crop production but also for pest and weed control, consumption of the seeds and for livestock feeding (Nyende and Delve, 2002). Farmers assess the different management options available to them, and adapt them to fit their own circumstances and production objectives. Growing Tithonia on-farm in available niches (around the field boundaries, for example) is one way of overcoming shortage of Tithonia and reducing the labour that would be needed if collecting the biomass from off-farm locations. For other farmers, the rapid decomposition of Tithonia makes it 'more like a fertiliser' (i.e. immediate effect, with little residual benefit) and therefore less attractive than farmyard manure (compost of animal, household, and crop wastes) which 'builds the soil' for the long term.

Recognition that innovation comes from multiple sources means that technology development must involve potential users from very early in the design process. To support this, extension must be more intimately linked with research to ensure that nascent technologies take fuller account of farmers' existing knowledge, practices, and priorities. 'Dissemination' would be of prototypes fully intended for modification or rejection by farmers and not of 'finished' products. However, by treating technology itself as politically neutral – i.e.: without knowing who benefits from existing practices, or who will likely benefit from changes – policy recommendations relating to soil fertility management will remain too vague to truly assist policy-makers, or be delivered through inappropriate channels to sectors unable to make use of them.

Implications of the policy environment on land management

While some of the constraints to crop production and examples of options available for alleviating soil productivity problems have been discussed at the farm level, many of the constraints facing farmers come from external forces, such as the (mis-) functioning of input and output markets, which can only be affected by modification of the 'policy environment'. For example, the bumper harvest reported in Kenya and Uganda in the 2001 short-rain season led to sale prices of maize that were often below production costs. In such situations, farmers face the prospective of losing money if they sell their maize to generate cash, but there is also no incentive for them to invest in their agricultural enterprises given the policy environment they operate within. Clearly, innovations need to address food security and livelihood sustainability, not just increased production as a good in its own right. Policy interventions that would rationalise input and output markets, and buffer smallholders from their volatility, should have as their goal a) increasing farmers' opportunities to innovate, and b) making investments back into agriculture attractive. One way in which such support could be given to smallholders would be by increasing investment in linking research, development, and extension with farm communities. In Kenya, the collapse of the formal extension network over the last five years has led to a shift towards farmer extension and farmer-to-farmer training through for example, farmer field schools. This increased reliance on information diffusion through social networks requires a better understanding of the role of social capital in innovation. In contrast, in Uganda, a newly privatised extension service is being piloted in test districts across the country, where parish level farmer forums feed through sub-county and counties to the district, which then contracts extension providers to provide the demanded services. This demand-led process has the potential to allow smallholder farmers increased access to markets, agricultural inputs and extension services and to improve access to information and technologies through the contracting of private sector service providers. This in turn will lead towards a more market orientated smallholder production sector.

References

Appleton S. 1998. Changes in Poverty in Uganda, 1992-1996, WPS/98-15, Centre for the Study of Africa Economies, University of Oxford.

Brookfield, H and Padoch, C. 1995. Appreciating Agrodiversity: A look at the dynamism and diversity of indigenous farming practices. Environment 36: 37-45

Delve, R. J. and Jama, B. 2002a. *Mucuna pruriens* and *Canavalia ensiformis* legume cover crops: Sole crop productivity, nutrient balance and management implications. In preparation

Delve, R. J. and Jama, B. 2002b. Evaluation of *Tithonia diversifolia* in biomass transfer systems in Eastern Uganda. In preparation

Farley, C. 1995 Smallholder knowledge, soil resource management and land use change in the highlands of Southwest Uganda. Ph.D. thesis, pp 332 University of Florida, US.

Getahun, A. 1991. Agricultural Growth and Sustainability: Conditions for their compatibility in the tropical east Africa highlands: In Agricultural Sustainability, Growth and Poverty Alleviation: Issues and Policies. Eds: S. Vosti, T. Reardon and W. von Urff, pp451-468. Washington DC: IFPRI

Giller, K. E., Cadisch, G., Ehaliotis, C., Adams, E., Sakala, W. D., Mafongoya, P. L., 1997. Building soil nitrogen capital in Africa. In: R. J. Buresh, R., Sanchez, P. and Calhoun, F (eds.) Replenishing soil fertility in Africa. SSSA Spec. Publ. 51. SSA, Madison, WI, USA pp. 151-192

Goldman, A. 1995. Threats to sustainability in African agriculture. Human Ecology 23, 291-334

Nyende, P. and Delve, R. J. 2002. Farmer participatory evaluation of legume cover crop and biomass transfer technologies for soil fertility improvement using farmer criteria, preference ranking and logit regression analysis in eastern Uganda. In preparation

Onesimus, S. et al. 1999. Needs and assessment for agricultural research in the Mount Elgon Hill sides farming systems.

Sanchez, P.A., Shepard, K.D., Soule, M.J., Place, F.M., Buresh, R.J., Izzac, A.N., Mokwunye, A.U., Kwesiga, F.R., Ndiritu, C.G. and Woomer, P.L. 1997, Soil Fertility Replenishment in Africa: An investment in natural resource capital, In: R. J. Buresh, R., Sanchez, P. and Calhoun, F (eds.) Replenishing soil fertility in Africa. SSSA Spec. Publ. 51. SSA, Madison, WI, USA

Smaling, E. M. A., Nandwa, S. M., Janssen, B. H. Soil fertility in Africa is at stake. In: R. J. Buresh, R., Sanchez, P. and Calhoun, F (eds.) Replenishing soil fertility in Africa. SSSA Spec. Publ. 51. SSA, Madison, WI, USA pp. 151-192

Paper presented at the INRM Workshop, Aleppo, Syria, 16-19th September, 2002

Contending with Complexity: The Role of Evaluation in successful INRM

Boru Douthwaite[1], Robert Delve[2], Javier Ekboir[3] and Steve Twomlow[4]
[1] Adoption and Impact Specialist, IITA, Ibadan, Nigeria
[2] Soil Fertility Management, TSBF Institute of CIAT, Kampala, Uganda
[3] Economist, CIMMYT, Mexico
[4] Global Theme Leader Water, Soil and Agrobiodiversity for Ecosystem Health, ICRISAT, Bulawayo, Zimbabwe.

Abstract

In contrast to reductionist approaches, Integrated Natural Resource Management (INRM) takes a holistic perspective that sees technology change as a complex social process, in which networks of agents that include, among other members, farmers, researchers, input suppliers, NGOs, extension agents and other government agencies generate and diffuse technologies. The technologies, networks and individual agents coevolve in response to emerging technical, social and economic challenges and opportunities. These changes affect adoption rates and who benefits and loses. More importantly, early identification of the forces that shape the evolution path of the technology and the network is essential for successful introduction and adoption of a new technology. Hence, it follows that rural development is an immensely complex process, with a high degree of non-linearity. Current 'best practice' economic evaluation methods commonly used in the CGIAR system, which attempt to establish a linear link between a project's outputs and regional or economy-wide impacts, struggle in this complexity. Indeed, such economic Impact Assessment (IA) is only valid if: 1) the causal link dominates from start of research to the measurement of impact; 2) there are no other factors affecting adoption and impact; 3) chance has no influence; and 4) inputs and impacts can be measured to an acceptable degree of accuracy. In practice replacement plant breeding is one of the very few CGIAR activities where these assumptions are likely to hold. A second shortcoming of economic IA is that it focuses largely on *ex-ante* and/or *ex-post* IA, but has little to offer in the area of monitoring and evaluation (M&E), despite M&E being identified as important in ensuring research projects actually achieve impact.

In this paper we review three case studies of M&E being conducted by three CGIAR centres in Africa. The case studies are: 1) Farmer participatory evaluation of legume cover crop and biomass transfer technologies for soil fertility improvement in eastern Uganda; 2) Impact pathway evaluation of integrated *Striga* control in Northern Nigeria; and 3) monitoring and evaluation of the dissemination of crop management options in Zimbabwe and Malawi. Although carried out independently, all three case studies focus on identifying the contributions of individual agents (e.g., farmers, researchers or input suppliers) to the adaptation and adoption of innovations, and the agents' motivations and perceptions that mould them. In each case study we examine the project, the creation of organisational capabilities and the changes that result from this understanding and conclude that participatory M&E has a vital role to play in helping projects respond early to farmers' evolving opportunities and needs. Finally, we argue that *ex-post* impact assessment should be based on the understanding of innovation processes developed during the M&E which shows which role each stakeholder played and why it made a difference, but without attempting to attribute a value to that contribution.

Introduction

The shortcomings of traditional economic impact assessment (IA)

Folklore in the CGIAR system tells of a golden period in the 1970s when the only financial constraint was the capacity to spend the money wisely. Back then, donors believed that "if a group of competent scientists were based in a developing country, were provided with excellent facilities, and were isolated from political pressure for several years, they were bound to generate useful new technologies" (Horton and Prain, 1989, p. 302). Those days have long gone. Not surprisingly donors started to perceive that isolation made CGIAR centres unresponsive to the needs of farmers and agro-industries, and started to demand evidence of priorities set jointly with the intended beneficiaries of the research, research impacts and the efficiency of research investments. In response to this pressure CGIAR centres invested much effort in the 1980s and 1990s in developing impact assessment methods (Ekboir, 2002). Much of this work was driven by the dominant social science approach in the CGIAR system, which remains grounded in traditional agricultural economics (Horton, 1997). These approaches rely on establishing a mechanical causal relationship between the costs and benefits of research.[4] 'Best practice' economic impact assessment is represented by the book *Science under Scarcity* (Alston et al., 1995), which is dismissive of other, less linear approaches as being "unlikely to yield any meaningful indications of the economic effects of research. … Therefore, they are not useful for informing allocation decisions." (p.501-2).

We contend that the predominance of traditional economic IA methods in the CGIAR system, often to the exclusion of a whole gamut of evaluation approaches developed in the field of evaluation, does not help solve donors' legitimate concerns about research relevance and impact. This is for two main reasons. Firstly, economic IA methods focus largely on ex-ante IA and then *ex-post* IA, but have little to offer in the area of monitoring and evaluation (M&E), despite M&E being identified as being important in helping research projects actually achieve impact. Secondly, economic IA, based as it is on linear models that link research inputs to outputs, is only valid if: 1) the causal link dominates from start of research to the measurement of impact; 2) there are no other factors affecting adoption and impact; 3) chance has no influence; and 4) inputs and impacts can be measured to an acceptable degree of accuracy (Ekboir 2002). In practice these assumptions can hold, as Table 5 shows, only for research activities developing 'minor' technological changes intended for use in 'simple' systems. Breeding of new plant varieties for irrigated areas that are already growing improved varieties of that particular crop, is one of the very few CGIAR research activities that would qualify. New varieties are simple to use because they are not new technologies but rather minor improvements of existing techniques along well known technological trajectories. Hence, the need for user modification and innovation, and therefore the unpredictability and non-linearity that this brings to IA, is limited. But since market and policy changes can affect adoption decisions in unforeseen ways, even relatively simple cases like the one described, are becoming increasingly complex due to globalisation and deregulation of agricultural markets.

Table 5: A diagram showing a two by two matrix of system versus technology complexity, examples of the research activities that fit in each matrix square, and where economic IA methods can and cannot work

	Complexity of system into which technology is introduced	
Knowledge complexity of technology developed	*Simple*	*Complex*
Complex "hard-to-employ"	Natural resource management in simple systems	Natural resource management in complex systems
Simple "easy-to-employ"	Plant breeding for irrigated systems	Participatory varietal selection in rain-fed systems

Key:

(dark grey)	Where linear innovation approach and conventional impact assessment could eventually work
(light grey)	Where complexity requires close research and user interaction and assumptions underpinning economic impact assessment breakdown

[4] Where mechanical is used in the sense of mechanism: a system with well defined and stable interrelations among variables that uniquely define the system's response to a change in one of the exogenous variables.

Box 1 gives a case study of a 6-fold increase in grain production in MERCOSUR[5] that was the result of the interaction of three technologies with social innovations and explains why impacts cannot be attributed to research outputs alone. The case study also shows that ex-ante impact assessment prioritised the wrong research area, illustrating the point that ex-ante impact assessment can only recognise technological trends once they have begun to emerge. Hence, institutions can only establish research programs in relatively known fields. If new trends are to emerge, researchers must be allowed to explore less known areas of research.

Box 1: A case study of impact where traditional economic IA does not work (from Ekboir, 2002)
In the 40 years between 1961 and 2001 production of maize, sorghum, sunflower, soybeans and wheat in MERCOSUR increased from 23 million tonnes to 152 million tonnes. The increase came about by farmers adopting three interdependent technologies: the introduction of soybeans in late 1960s, zero tillage and improved germplasm. Soybean production led to an intensification of agriculture, which caused serious soil degradation. A number of technical solutions were proposed to solve the problem, including zero tillage and terracing. At the time, researchers identified terracing as the more promising option, and as a result soil conservation projects neglected work on zero tillage. Nevertheless, by 1985 viable zero tillage systems had been developed by a network of agents, including agrochemical companies, a few public sector researchers, farmers and agricultural machinery manufacturers. In the late 1980s researchers and farmers, with support from Monsanto, created associations to promote zero tillage. Adoption, however, remained low until the early 1990s because the herbicide glyphosate (a key component of the package) was expensive. Then, a change in corporate policies helped bring about a fall in price from US$ 40 per litre to US$ 10 per litre. The new relative prices combined with a very effective diffusion policy organized by the association caused adoption to explode (Ekboir, 2001). Zero tillage reduced production costs, reversed soil erosion and allowed an expansion of agriculture into previously marginal lands. Without zero tillage, grain production would have had to be abandoned in many areas.

The impact of these technologies cannot be separated. Without zero tillage, the impact of improved germplasm would have been very small, as zero tillage was necessary to stop soil erosion and improve water management. At the same time, new and improved germplasm increased the profitability of zero tillage, fostering adoption. But adoption only exploded when a key input produced by a private firm became affordable.

Economic IA assumes a mechanical link between research outputs and the benefits, and then attempts to separately attribute impact to the different components of the package. However, this is not possible in cases like this characterized by multiple interactions and feedback loops among several physical and social components and agents. Hence, traditional economic IA is not able to evaluate the research that contributed to the impact, because, for example, without the reduction in the price of glyphosate the impact would have been small. But the price reduction was completely unrelated to plant breeding or development of zero tillage.

In addition to the failure of ex post economic IA, ex ante impact assessment also failed by wrongly prioritising terracing as the most viable technical solution to soil degradation. As a result resources were siphoned off that might have otherwise hastened the adoption of zero tillage. Only after terracing proved to be unsustainable was zero tillage recognised as the best option.

Evaluation that can deal with complexity

Complex adaptive systems are characterized by three features: several interactions among agents and processes, strong feedback loops and intrinsic randomness. Because of these three features, these systems are essentially unpredictable in the long run, even though limited predictability is possible in the short run. Although outcomes cannot be predicted, key factors that influence the probability of success of agricultural innovation processes have been identified. These are the emergence of strong and flexible networks, the adoption of participatory research and diffusion methods where farmers play a key role,

[5] MERCOSUR is an imperfect customs union formed in 1995 by Argentina, Brazil, Paraguay and Uruguay.

flexible evaluation and monitoring routines in public research institutions and access to internationally generated information (Ekboir and Parellada 2002). Effective monitoring and evaluation routines of these factors that result in rapid corrective measures can greatly increase the chances of large impacts.

In addition to traditional IA, the CGIAR system needs innovative M&E approaches that aid a continuous redesign of on-going research projects (including 'learning by doing', 'learning by learning', mapping of innovation networks, creation of organizational capabilities and adaptive management). The importance of M&E to good, adaptive, project management is recognised as key to successful Integrated Natural Resource Management (Sayer and Campbell, 2001). Furthermore, donors at the February 2002 CGIAR Impact Assessment Conference urged centres to focus more on M&E that contributes to institutional learning and change, and less on *ex-post* IA of successes for publicity purposes. The following are three cases studies of recent and on-going M&E exercises to show the types of knowledge that this work can produce, and how it can feed back into the research and priority setting process. We then follow with a discussion of how inclusion of M&E can build the foundation for more plausible *ex-post* IA and be used as an essential tool in priority setting.

Case Studies of M&E being carried out by CGIAR Centres

Conceptual map of the innovation process

All three case studies described in this section implicitly assume the conceptual map of the technology development and adoption process shown in Figure 1, and therefore the case studies are described with reference to the model. The model recognises four phases in the innovation process:

Development Phase— Innovators (e.g., researchers, farmers, input suppliers or other agents working together or in isolation) are permanently searching for new technological or economic alternatives to achieve their objectives (which may include improved livelihoods for farmers or professional recognition for researchers). Problem diagnosis with the intended target group(s) is part of this process. When an alternative is identified, the innovators develop 'best bet' integrated solutions.

Start-Up Phase—The network of early developers take these 'best bet' options and demonstrate them to individual and/or a network of farmers, in the hope that farmers will see that at least some aspects hold out a 'plausible promise' of being benefit to them, sufficient to motivate at least a few to contribute their own time and land in experimenting.

Adaptation Phase—Experimenting farmers and other agents work together to adapt and refine the 'plausible promise' into something better; something that is seen to work and make sense to the wider community;

Expansion Phase—Adoption levels expand as the community begins to adopt their locally-constructed solution(s). This might be an integrated package and/or a single component of the 'best bet' options originally introduced.

While necessary in all phases, M&E is particularly important in the adaptation phase to help ensure the innovations and farmer adaptations can be captured and incorporated into the research process.

Implicit to this conceptual map is the premise that once developed, a complex technology that is widely adopted in a pilot site, will scale-out to other, similar, communities through multi-actor interactions. However, scaling-out can be accelerated by a properly designed extension approach that speeds up both the knowledge spread and the experiential learning that is necessary to construct the technology in communities elsewhere.

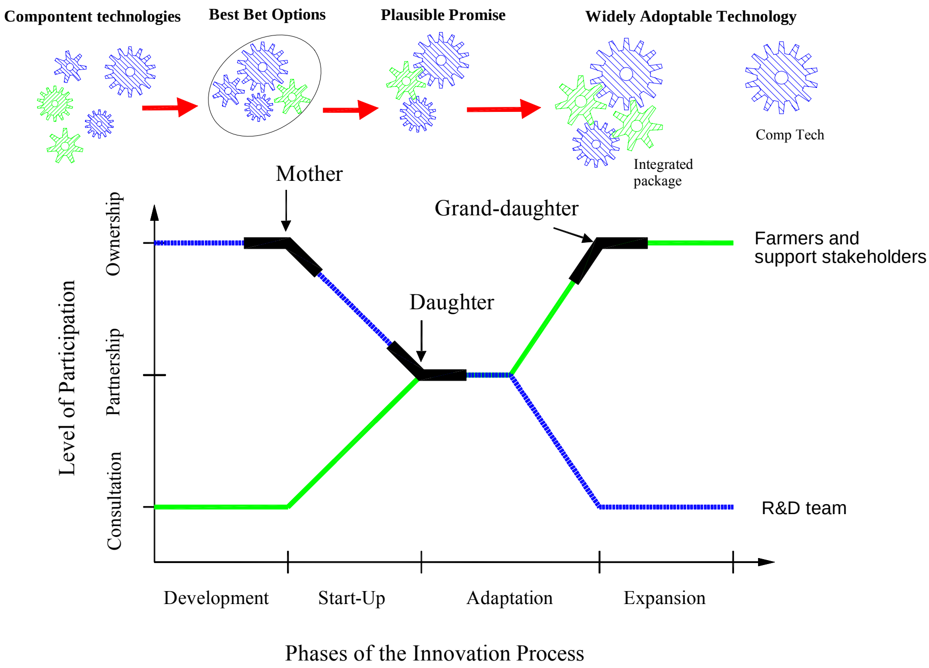


Figure 1: Conceptual map of the development and adoption process adopted in the case studies

TSBF-CIAT: Farmer participatory evaluation of legume cover crop and biomass transfer technologies for soil fertility improvement in eastern Uganda

Introduction

In late 1998, the Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture (TSBF-CIAT) introduced legume cover crop (LCC) and shrub species, proven to improve soil fertility, into two sub-counties of Tororo District, in eastern Uganda. These legume species were: *Canavalia ensiformis; Crotalaria grahamiana*; *Dolichos lablab; Mucuna pruriens; Tephrosia vogellii;* and *Tithonia diversifolia*. TSBF-CIAT began by setting up several on-farm trials, together with 40 participating farmers. The purpose of these trials was to validate and demonstrate the effectiveness of the LCCs and shrubs as, for example, cover crops to control weeds, or to improve soil fertility, by, in some cases, biomass transfer (BT) from one field to another. These activities were backstopped by project field officers, as well as, by the district extension services of the government. To reach more farmers a range of approaches were implemented, extension agents were trained on the use and management of the technology, innovative farmers were identified in each sub-county and trained, farmer-to-farmer extension formed an important component of the program. Many study and exchange tours were organized to enhance farmer-to-farmer learning and adoption of the technologies promoted. By the end of 2001 over 2000 farmers had established their own evaluation trials as a result of extension visits and farmer-trainer visits and from exchange visits to demonstrations sites.

Materials and methods

TSBF-CIAT conducted a farmer participatory evaluation of the LCC and BT species after seven seasons in December 2001 and January 2002 with 21 farmer groups, representing 234 farmers (92 male, 142 female). The farmer groups were purposively selected on the basis of having several seasons' experience with the legumes and their management. Group discussions and key informant interviews were then held to:

- Establish farmers' assessment of the legume species for soil fertility improvement;
- Identify farmer innovations with respect to the use and management of the legumes;
- Identify farmers' evaluation criteria when comparing between legumes;
- Conduct a matrix ranking based on these criteria.

Results and discussion

Farmers identified a number of positive and negative characteristics of each legume (**Table 6**). Some of the positive aspects correspond to innovations made by farmers during their trials (**Table 7**). Generally, the innovations show that farmers are seeking to increase the benefits of the technologies by finding alternative and dual-purpose uses for the legumes, other than for soil fertility or weed suppression. These include attempting to: eat the seed and leaves in sauce (*Lablab*, *Mucuna*), to control crop pests and diseases (*Crotalaria, Canavalia, Tephrosia*), catch fish (*Tephrosia*) and curing human ailments (*Tithonia*). Other innovations, for example, border planting, are designed to reduce the cropland taken by the legumes. An indication that farmers had learnt to value the legumes was that some groups gave them local names. One group called *Canavalia* 'Yathipendi' meaning 'medicine for banana' while another group, that was dominated by old men, identified it as 'Akengu ka Angu' meaning 'trap for the Hyena'. Tephrosia was locally known as 'Yathi fuuko' (medicine for mole rat) or 'Yathirechi' (medicine for fish). *Tithonia diversifolia,* was locally referred to as 'Mawuwa' but with no particular meaning attached to the name. It should be noted, that in some cases farmers knew the species before TSBF-CIAT established the trials but were not aware of their potential uses and that some of the names, innovations and discoveries occurred outside the learning cycles that took place as a result of the project trials.

Table 6: Farmers' assessment of the legume species

LCC/shrub	Positive aspects	Negative aspects
Mucuna Local name: none	Improves soil fertility Suppress weeds effectively Produce high biomass Quick maturing	Not edible Not good for intercropping (Climbs the crops) Requires high labour for clearing and incorporation Can harbour snakes and wild cats if planted near the home
Canavalia Local name: Yathipendi (medicine for banana) or Akengu ka angu (trap for the hyena)	Improves soil fertility Has fodder value Suppresses weeds Easy to multiply (high seed production) Good for intercropping	Not edible
Crotalaria Local name: none	Improve soil fertility Suppress weeds	Has pest problem – scarring caterpillars
Tephrosia Local name: Yathi fuuko (medicine for mole rat) or Yathirechi (medicine for fish)	Improves soil fertility Control mole rat	Has pest that eats the pod, hence poor seed formation
Lablab Local name: none	Improves soil fertility Has fodder value Suppresses weeds	Difficult to obtain seed
Tithonia Local name: Mawuwa	Improves soil fertility Malaria & stomach ache medicine Has pesticidal properties Fodder for goats	It is a weed

Table 7: Farmer modifications and innovations to management and use of legume species

Legume species	Modification to management and use
Mucuna	Attempts to cook it and eat the seed in sauce
	Efforts to crush seed to make animal feed
	Good feed for goats, cattle and rabbits
Canavalia	Used to scare-off hyenas in the olden days, and monkeys these days
Crotalaria	Boundary planting around the homesteads instead of researcher-recommended intercropping with maize or planting as one season fallow crop
	Intercrop with beans to control nematodes and other bean diseases.
	Seed put together with bean seed during storage to control bean storage pests
Lablab	Seed and the leafy vegetation eaten in sauce
Tephrosia	Leaves are crashed, poured into rivers and streams to catch fish
	Doubt on its effectiveness in controlling the mole rat
Tithonia	Leaves used for treatment of stomach ailments and fevers

Farmers were also asked to make explicit the criteria they used when evaluating the legumes

Table **8**) and the overall farmer ranking, developed using a ranking analysis tool with the 21 groups, is shown in Table 9. The rank order from the most to the least preferred was *Mucuna, Tithonia, Canavalia, Crotalaria, Lablab* and *Tephrosia*.

Table 8: Criteria used by farmers in ranking LCC and shrub species

Criteria	Reason of criterion
Yield increase of crop after fallow or intercrop	Weight of grain, bunch, fruit etc
Crop vigour of crop after fallow or intercrop	Health
	Greenness of leaves
Soil fertility increase	Change of soil colour to dark
	Depth of soil increased
	Ease of ploughing
	Soil erosion control
	Moisture retention
	Time taken to cause significant fertility increase
Ease of germination, establishment & seed production of the LLC or shrub	More seed produced in a short time & viable for a longer time.
	Small seed difficult to collect
Multiple uses of the LLC or shrub	The number of other additional uses from the LCC or shrub e.g. firewood, medicine, fodder etc.
Suitability for intercropping	Intercrop compatibility i.e. minimal competition of the LCC or shrub with the crop
Ability to control weeds	Dense canopy formation which suppress undergrowth
Amount of biomass production	Number of leaves
	Size of leaves
	Ground coverage
	Shorter maturity period
Labour requirement for clearing, uprooting, cutting and incorporation	Ease of bush clearing, uprooting, cutting stems and leaves & then incorporation into the soil

Table 9: Overall matrix ranking of the LCCs and biomass transfer (BT) species based on the criteria (from 21 farmer groups)

Criteria for ranking	LCC and shrub species					
	Mucuna	*Canavalia*	*Crotalaria*	*Tithonia*	*Tephrosia*	*Lablab*
Yield increase in crop	2	4	3	2	5	4
Crop vigour of crop	1	4	2	2	5	5
Soil fertility increase	2	4	4	2	5	5
Ease of establishment	2	3	5	2	6	5
Multiple uses	5	5	5	4	4	4
Suitability for intercropping	4	2	2	3	3	5
Ability to control weeds	1	4	3	3	6	4
Amount of biomass production	2	4	4	2	5	5
Labour requirement	3	1	3	4	4	4
TOTAL	22	31	32	24	43	41
RANK	1	3	4	2	6	5

For the 21 groups a cumulative probability was plotted against the ranking order given by each group (Figure 2). The area under the lines for the different LCC and BT species is directly related to its ranked popularity. For example nearly all the groups rated *Mucuna* either first or second, giving a large area under the *Mucuna* line, while most farmers rated *Tephrosia* either fifth or sixth giving a much smaller area under the Tephrosia line. What Figure 2 shows is that *Mucuna* is clearly the most popular, *Lablab* and *Tephrosia* are almost universally unpopular and have a low probability of being accepted in any village, while *Crotalaria*, *Canavalia* and *Tithonia* are moderately popular with little to distinguish between them. This analysis has been confirmed using a logic regression analysis (Nyende and Delve 2002).

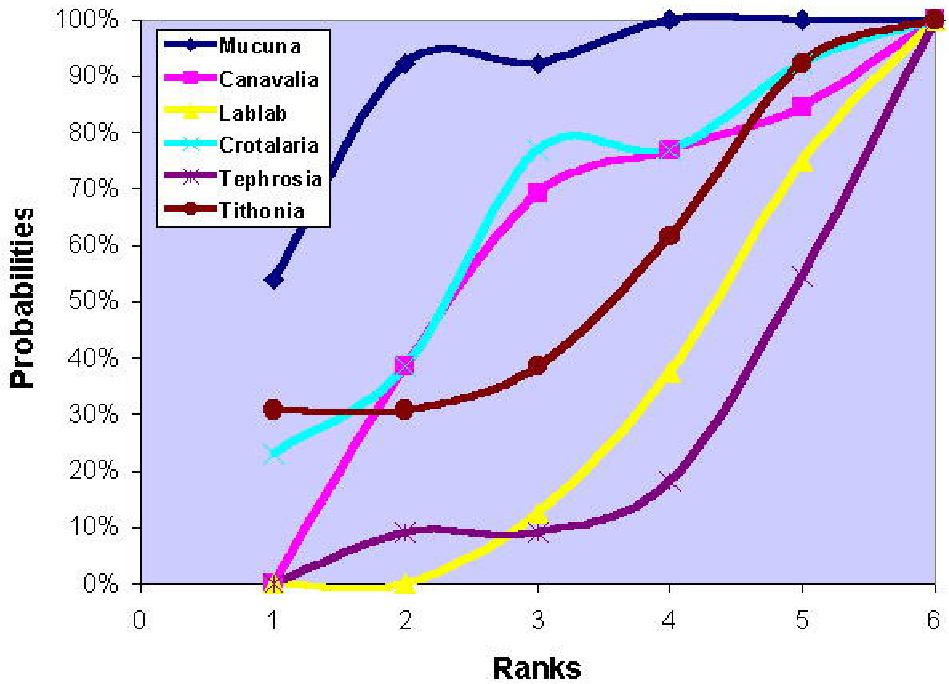


Figure 2: Comparison of the acceptability of LCC and BT species by plotting cumulative probability against the ranking given by the different groups

Discussions with farmers during the group assessments and ranking exercises, as well as open and probing questions, gave insights into the constraints to farmer adoption. Fallowing the land is not possible where small land sizes or high population densities exist and where seed supply for these legume cover crops is not good. In eastern Uganda, where the population pressure is much lower and where natural fallowing is still part of the farming system, the opportunities for improved fallowing or biomass transfer is much larger. Even so, farmers commonly cite difficulties in finding the labour required for collecting or incorporating biomass. Also, many farmers are very reluctant to use land and effort without producing a crop, even if future benefit justifies the investment. This is because most farmers' main priority is food production, and they are very risk adverse. As an adaptive research farmer commented, '*Its better to have even one gorogoro tin of maize [from a depleted field that was planted with maize] than to be guaranteed no maize at all this season by planting a cover crop we can't eat*' (Ramisch, pers. Comm.).

The next stage in this adaptive research process involved the systematisation of information from the M&E, detection of knowledge gaps, and the identification of potential research questions during follow-up community meetings attended by the farmers, extension agents, NGO and CIAT staff. During these meetings the results of the participatory evaluation were discussed and this led to the identification of new research questions that needed to be addressed. For example, *Lablab* was identified as a very promising multi-purpose legume but the variety the community had was not producing seed. As a result new photoperiod insensitive and early flowering germplasm from Australia and Africa is now under-going on-station evaluation.

After identifying new research questions the different partners then agreed on how to address the issues. They did this by:

- Identifying key farmers to conduct adaptive research on behalf of the community. These farmers will establish a range of experiments, and will be responsible for monitoring the experiments and reporting back to the whole community on the results.
- Applied research questions to be addressed by National agricultural research partners, through an array of methods from on-station research to on-farm research.
- Strategic research questions to be addressed by CIAT, TSBF, and other partner international research institutes through an array of methods from, strategic on-station research to on-farm research.

Conclusions

The most important outputs of the M&E process was the identification of the criteria used for species selection and the farmers' innovations. Both provided essential feedback to the participatory action research approach as they reflect the opportunities and constraints of the production systems of the farmers and raise many new areas of research, opportunities of evaluation of new technologies and species, and the better targeting of existing information. The M&E has shown that farmers adapted technologies introduced primarily for soil fertility replenishment in an attempt to fulfil a much wider range of production objectives, leading to the conclusion that a single-use technology had little chance of large-scale adoption. This has resulted in a major rethink by researchers and partners of the methodology and approach taken and the types of research conducted in the project.

IITA: Impact Pathway Evaluation of Integrated Striga Control (ISC) in Northern Nigeria

Introduction

Striga hermonthica is a parasitic weed that attaches itself to the roots of cereals (e.g. maize, sorghum, millet and rice), diverting essential nutrients and leaving the host stunted and yielding little or no grain. The weed is the severest biological constraint to cereal production in sub-Saharan Africa, infesting almost

21 million hectares of land causing millions of dollars of damage (Sauerborn, 1991). Farmers world-wide call it ‘witch’ weed, because it does most of its damage before it emerges from the soil.

Research at IITA and elsewhere is showing that *Striga* control is possible using an integrated approach that attacks *Striga* from several sides at the same time. A key component of this Integrated Striga Control (ISC) approach is the use of a legume crop (e.g., soybean, cowpea, groundnut) that induces a high proportion of *Striga* seeds to germinate, which then die because they cannot parasitize legumes. This is called ‘trap cropping’. To be effective, legume trap crops must be planted much more closely than farmers usually plant their legumes, and should be used together with *Striga*-resistant cereals, seed cleaning to remove *Striga* seed, crop rotation, weeding of the *Striga* plants before they set seed, and improved soil fertility.

Since 1999, a research project at IITA has been working in four villages in Northern Nigeria using participatory research approaches to develop locally-adapted integrated Striga control (ISC). The villages where chosen on the basis of having severe *Striga* problems. Two group meetings were held, first to carry out a problem consensus to rank *Striga* in relation to other problems, and then to design experiments to evaluate the options for *Striga* control. The R&D team has provided training to improve farmers’ understanding of *Striga*. The work began with 19 participating farmers (Schulz et al. in press).

Materials and methods

M&E has been built into the project from early on, based on the project impact pathway shown in Figure 3. The impact pathway describes how the project expects the output—validation and adaptation of ISC options in farmers’ fields—might lead ultimately to the project goal of improved livelihoods for the 100 million people in Africa that are affected by *Striga*. The shaded boxes are the intermediate outcomes that the project is monitoring. The unshaded boxes will be evaluated in the *ex post* impact assessment some time after the end of the project.

The project is using two published approaches to monitor and evaluate the delivery of the intermediate outcomes shown in Figure 3. The first is the ‘Follow the Technology’ (FTT) approach (Douthwaite et al. 2001; Douthwaite 2002) that sees technological change in general, and early adoption in particular, as an evolutionary process in which stakeholders generate novelties (i.e., make modifications; innovate), select those that appear to work and promulgate the results. The Follow the Technology approach involves, as the name suggests, following new technologies and knowledge as they are adopted. The FTT approach focuses on identifying modifications, selection decisions (i.e., whether farmers decide to adopt a modification), and promulgation processes. Key to the direction and nature of an evolutionary process is the environment, hence the FTT approach pays particular attention to seeking explanations for novelties generated, selection decisions made and the nature of promulgation paths to understand the socio-economic and cultural factors affecting farmers’ learning and decision making processes. By paying particular attention to who is, and is not, modifying and adopting, as well as identifying conflicts arising from adoption, the FTT approach is able to identify negative as well as positive consequences.

The project will use the Sustainable Livelihoods Framework (SLA) (Scoones, 1998), summarised in **Figure 4**, to guide an evaluation of whether adoption of ISC is having any impact on peoples’ livelihoods. This will be done by constructing case studies of individual households, purposively selected to be representative of poor, medium and rich households in the four villages.

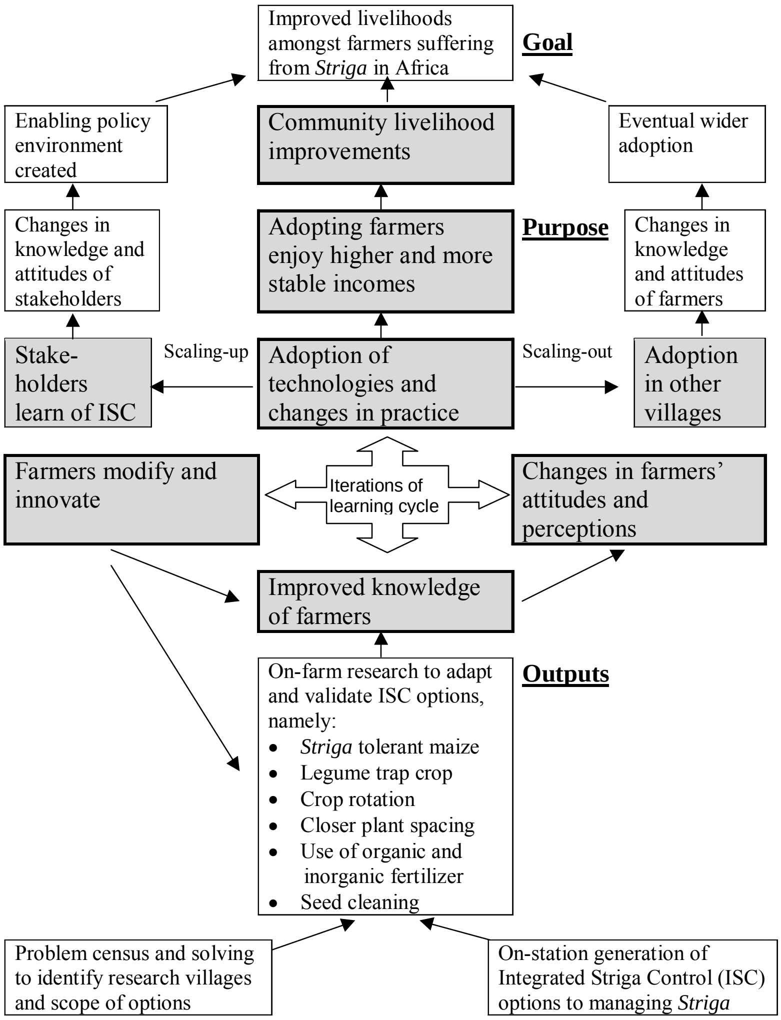


Figure 3: Impact pathway for an Integrated *Striga* Control (ISC) Project in Northern Nigeria

From October 2001 to January 2002 a survey was carried out to identify farmers who had adopted at least one component of ISC from the participating farmers. A total of 245 expansion farmers were identified in this way. The positions of the 44 participating farmers' experimental plots and the subsequent 'expansion' plots were then marked using a hand-held GPS and plotted using the geographic information systems (GIS) program ArcView (ESRI, 1999). A data sheet was completed to record what was planted in the fields, and modifications made to the recommended package shown in Figure 3. From February to June 2002 an in-depth survey was then carried out of a random sample of 149 of the participating and expansion farmers. The survey sought explanations for farmers' adoption and modification decisions, his or her understanding of ISC, and to find out where the farmer received the technologies from, and who he or she has passed them on to. The questionnaire specifically asked whether farmers passed on any of the agronomic recommendations, e.g., close legume spacing, in addition to distributing seed. In this way the FTT approach monitors and evaluates changes to five of the boxes shown in Figure 3, that is, changes in farmer knowledge and perceptions; modifications; adoption; and the spread from the pilot villages elsewhere (scaling-out).

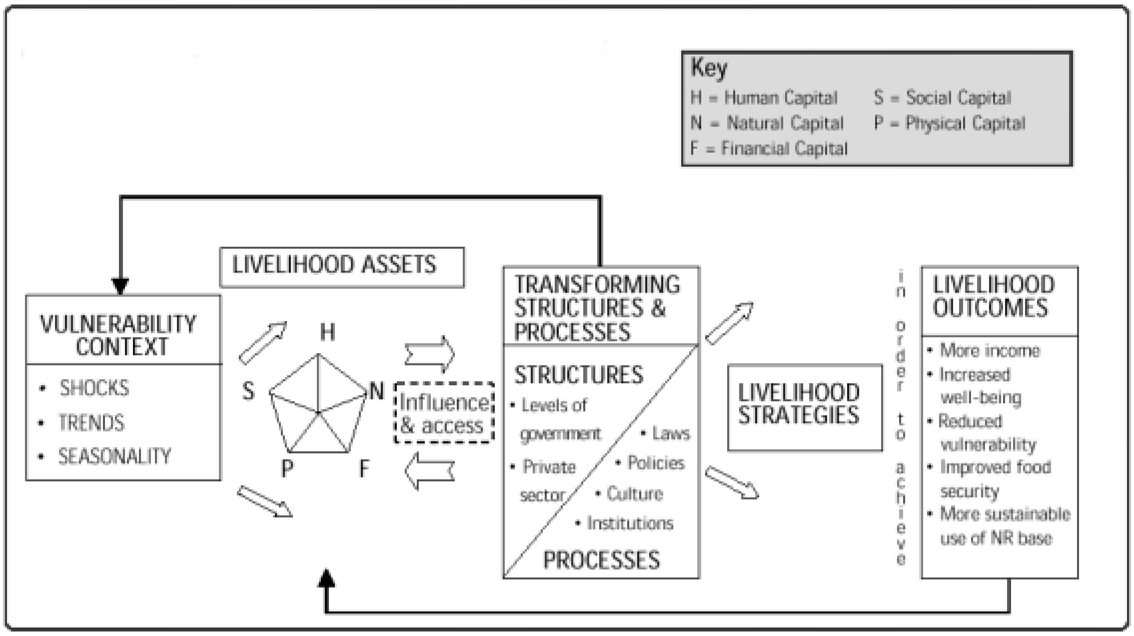


Figure 4: The Sustainable Livelihoods Framework

Findings and Discussion

Table 10 shows that over half of the farmers had made at least one modification to researcher-recommended management when they adopted aspects of ISC. Most of these were to reject the researcher-recommended sole-cropping and closer plant spacing, in particular for soybean. The latter was largely because recommended soybean row spacing was 35cm, while in most farmers' fields row spacing was fixed by the local animal-driven plough at 70cm. One farmer, however, came up with the innovative approach of planting two rows per ridge, shown in
. It shows that the farmer has understood the principle of suicidal germination and the need for higher soybean root density. The project has subsequently adopted this practice because it reduces the cost of establishing legume trap crops.

Table 10: Modifications made to researcher-recommended Integrated Striga Control (ISC) package

Modification	f
No modification	75
Planting widely spaced single rows of cereal in soybean (Gicci) perpendicular to the ridges	37
Wider row spacing	15
Strip cropping (e.g. 2 rows cereal, 4 rows legume)	11
Intercropping (e.g. maize, sorghum and groundnut in same field)	6
Relay cropping (e.g., cowpea planted into established maize field)	4
Planting two rows of soybean on 1 ridge	1

n=149

Farmers' rejection of sole cropping has negative implications for *Striga* control because mixed cropping with cereals (gicci, strip, intercropping and relay) is a concern to the project because it means that Striga will grow and flower each year in the field thus replenishing the seed bank. The reasons farmers gave for continuing with mixed cropping is that it reduces risk, and gives a higher overall yield. Both reasons are valid, although the second is only true with low fertilizer use that necessitates wide cereal plant spacing, leaving room for a legume in-between. However, researcher-managed trials have shown that a sole-crop legume followed in rotation with close-spaced sole-crop maize with moderate fertiliser application rates gives better *Striga* control and much higher yields than farmers' practice, and is more profitable (Schulz et al. In press). In an effort to bring farmers' and researchers' perceptions and understanding closer together the project is planning to carry out a participatory budgeting exercise at the end of the 2002-cropping season to help farmers more clearly see the economic benefits of sole-cropping and legume-cereal rotations, and for researchers to better understand the benefits of mixed cropping. This would not have happened without the data from the monitoring and evaluation.

Figure 5: Farmer in Northern Nigeria who is experimenting with planting soybean on either side of the row so as to increase soybean planting density

Figure **6** is an example of maps drawn for each of the four villages where the experimental plots were first set up, showing the spread of the ISC crop varieties, and one of the management recommendations—the close planting of legume trap crops. Other maps are possible showing the adoption of the other components of ISC. However, what these particular maps show is firstly the majority of farmers are adopting closer spacing of legumes, showing that knowledge about how to use the trap crops is spreading as well as the seed. Secondly, the maps show that the adoption pattern is different in different villages. In Kaya village, for example, adoption is clustered around the participating farmers and their fields, while in Mahuta, aspects of ISC have moved up to 40km. The project is now planning to develop a ISC extension approach built on fostering these indigenous scaling-out mechanisms. Again, without M&E the project would not be following this path.

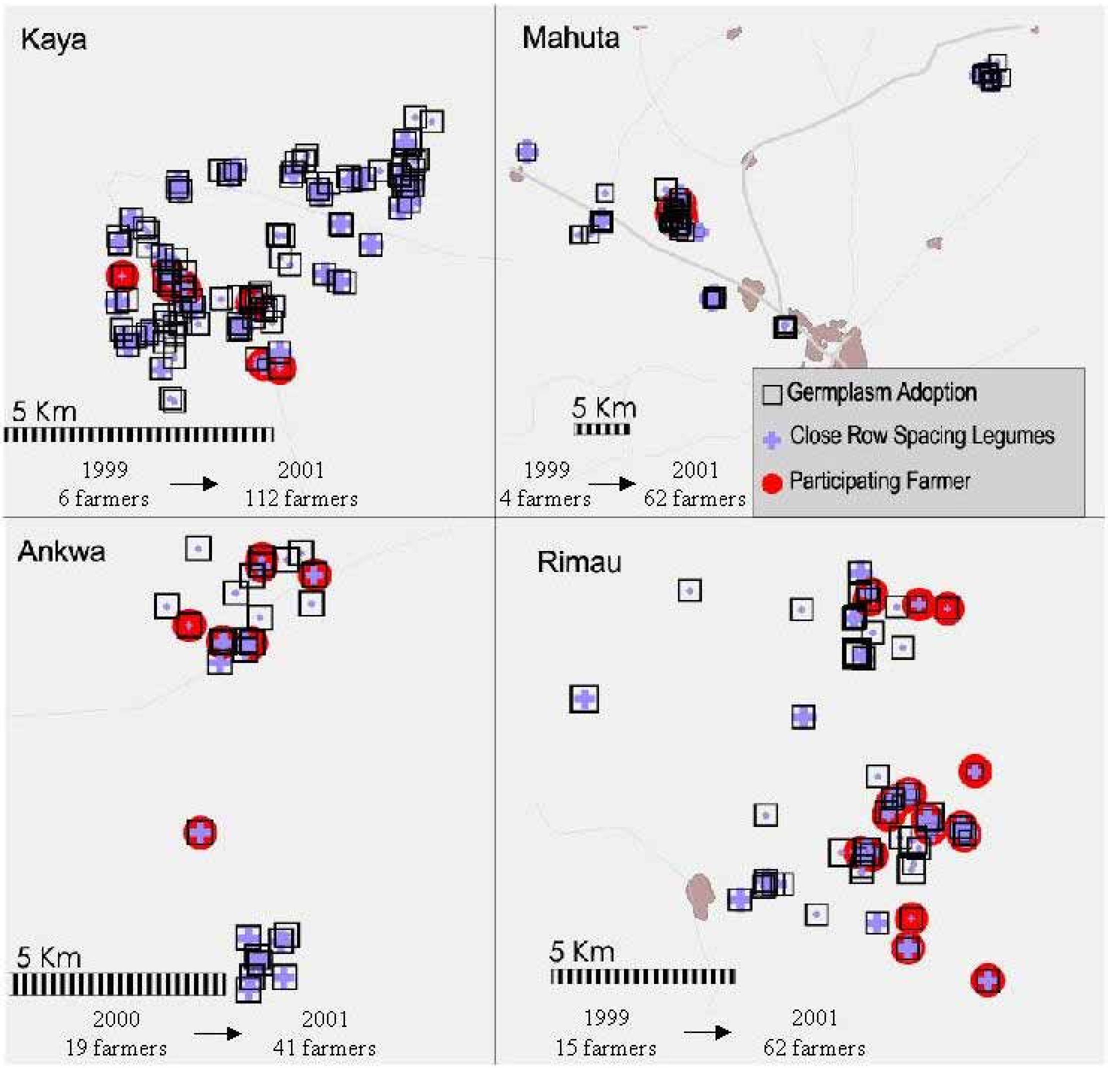


Figure 6: Adoption and spread of integrated *Striga* control technologies in four villages in Northern Nigeria. Each point represents one farmer's field. Two or more legends superimposed on one point mean that the farmer adopted two or more technologies

Conclusions

M&E has helped give the ISC project a much clearer impact focus through the process of defining the project's impact pathway. The M&E findings have redirected research efforts in a number of ways, including through the incorporation of farmer innovations in the recommended basket of options; the decision to carry out a partial budgeting exercise to bring farmers' and researchers' perceptions of the pros and cons of mixed versus sole cropping closer together; and by providing the understanding of adoption processes necessary to develop an effective ISC dissemination approach.

More practical crop management options for potential dissemination to women-headed households in Malawi and Zimbabwe - A Case Study by ICRISAT-Zimbabwe

Introduction

In 1998, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and its partners in Malawi and Zimbabwe began a comparison of different Farmer Participatory Research (FPR) approaches being used by various organizations in Malawi and Zimbabwe. A key objective was to compare the effectiveness of different methodologies in the development and testing of soil management technologies for resource-poor farmers, particularly women farmers. A second objective was to investigate the contribution that crop systems simulation modelling could make to FPR. To accomplish the objectives the project tested FPR methods at each of six case study sites, three each in Malawi and Zimbabwe. The various methods involved varying degrees of farmer participation: traditional research-led, researcher-led with farmer input, and farmer-led with research input.

The project tested four hypotheses:

- The provision of a broad range of soil water and nutrient management options is better than blanket fertiliser recommendations currently offered by government extension services, which are 3 to 8 times higher than the rates that farmers usually apply;
- Recommending less inorganic fertilizer and more manure and legumes to women farmers would increase their adoption rates, and thus improve productivity and food security.
- Uptake of technologies would vary with the wealth of the household and gender of the household head.
- Adoption would follow a cycle starting with a low rate of inorganic fertilizers and manure and increase through learning-by-doing and learning-by-using.

Materials and Methods

At start-up the project invested heavily in training activities with research and development staff from the different partner institutions to introduce the various concepts of the participatory research process and simulation modelling. However, the short duration of the project meant that much of the problem identification and selection of best bets occurred prior to the training. The 'best bet' technology options were selected in part through an exercise in systems analysis conducted in September, 1999, based on crop simulation modelling and resource-constrained scenarios that incorporated realistic levels of farmer resources. Socio-economic data and the judgement of agronomists and economists were used to devise resource-constrained scenarios (e.g., trade-offs for allocation of labour and resources among different farm management components: timely planting and weeding, fertilizer and manure). Simulation was then used to evaluate different scenarios, with the goal of maximizing return from the whole farm while limiting risk. The best bet options chosen included a range of legume intensified systems (Chamango, 2002; Twomlow et al., 2002), moderate inorganic fertilizer use alone or in combination with extra weeding (Dimes et al., 2002), and manure (Murwira and Kudya, In press).

Throughout the projects life various formal and informal workshops were held in both Malawi and Zimbabwe to introduce various concepts of the participatory research process and simulation modelling to researchers, extensionists and farmers. On-farm experimentation with the best bet options was then conducted over the 1999/2000 and 2000/2001 growing season at the six case study sites. Each case study village had a research-led, farmer-input trial and either a farmer-led, research-input and/or a research-led, traditional trial. The choice and implementation of the best bet options and the FPR approaches varied depending on the experiences of the local team.

To fully understand the household labour implications and farmer perceptions of the different technologies being tested at the six field sites field days were held on a seasonal basis and farmers perceptions of each technology were solicited using a range of participatory tools, such as matrix ranking. These field days were followed up by a series of focus group discussions between March and May 2001, with participating farmer groups in both countries (Rusike and Twomlow, unpublished field notes; Ncube and Twomlow, 2001). At each of these meetings the farmers were asked to describe their cropping calendar in relation to local soil taxonomies, the labour resources used for each task, and local input and output prices, the technologies they had been evaluating, and what, if anything they had adopted or adapted (see

). This information was then used to construct a final adoption survey from which partial budgets for each technology were determined, from which net benefit curves and a marginal rates of return analyses were calculated to identify what financial benefits might accrue for a rural household and the potential risks of the different technologies. Based on this information a whole farm mathematical programming model was constructed to determine profitability of the improved soil water and fertility management options relative to other investment options given the household resource constraints and preferences for risk, and thus identify constraints to adoption. The model was set up to maximize net revenue of the whole farm subject to resource constraints. The model captured risk as the minimum quantity of staple food grain (1 ton of maize, sorghum or millet grain per 6 family members) that the household needs to produce to meet its food requirements for the year. The model was then run for different resource categories of farmers using the gender of household head as the proxy indicator.

Figure 7: Malawian collaborator describing the field trials she has hosted over the last two seasons

Results and Discussion

The FPR trials indicated significant yield increases result from use of best-bet options compared to farmers' practice, including small quantities of fertilizers linked to weeding, legume rotations and intercrops and anaerobically-composted manure.

Marginal rate of returns analysis showed that best bet technologies offered significant benefits to farmers and had returns which exceeded 100%, which is usually assumed to be the minimum required for smallholders to widely adopt this type of agricultural technology (see
Table 11 and
Table 12 for example marginal rate of return analyses for legume best bet trials in Malawi and Nitrogen by Weeding Trials in Zimbabwe). However, farmers' evaluation of technologies, using matrix ranking exercise during field days, showed that they may still not adopt the technologies despite their competitive marginal rates of returns shown in
Table **11** because of resource constraints, access to input and output markets, risk and food security (Table 14).

Table 11: Marginal returns analysis of undominated treatments tested in legume trials, Malawi, 1997/98-1999/2000

Chisepo		Mangochi		Dedza	
Treatment	**Return (%)**	**Treatment**	**Return (%)**	**Treatment**	**Return (%)**
Unfertilized maize	n.a.	Unfertilized maize	n.a.	**Unfertilized maize**	n.a.
Mucuna-maize	1562	*Mucuna*-maize	675	*Mucuna*-maize	135
Maize-Tephrosia	Dominated	Maize-*Tephrosia*	Dominated	Bean-maize	1743[a]
Maize+pigeon pea	Dominated	Maize+pp unfertilized	Dominated	Maize/*Tephrosia*	101[b]
Groundnut+pp	Dominated	Groundnut + pp	44	Maize+legume unfertilized	Dominated
Maize+fertilizer	60[a]	Maize+fertilizer	Dominated	Maize+fertilizer	Dominated
Maize+pp+ fertilizer	152[a]	Maize+pp+ fertilizer	Dominated	Maize+legume+ fertilizer	Dominated

n.a. Not applicable because it is the control treatment
Dominated Treatment marginal rate of return worse than control
a. If rule out *Mucuna*-maize system
b If rule out *Mucuna*-maize and bean-maize systems

Table 12: Marginal returns analysis of undominated treatments tested in fertilizer by weeding trials, Zimbabwe, 1997/98-1999/2000

Treatment	Marginal rate of return (%)
0 kg/ha Nitrogen-1-weeding	n.a.
18 kg/ha Nitrogen-1-weeding	218
18 kg/ha Nitrogen-2-weeding	380
35 kg/ha Nitrogen-1-weeding	471

Table 13: Comparison of acceptability of technology options tested in the trials, Malawi, 1997/98-2000/2001

Best Bet Option	Agronomic[1] Acceptability	Economic[2] Acceptability	Farmer [3] Acceptability
Unfertilized maize	5	6	5
Maize + area specific fertilizer	2	4	7
Maize+pigeon pea	3	2	2
Maize+pigeon pea+area specific fertilizer	1	3	6
Groundnut+pigeon pea	6	5	3
Maize+*Tephrosia*	4	7	4
Mucuna-maize rotation	7	1	1

1 - Agronomic acceptability in terms of yield performance
2 - Economic acceptability in terms of marginal rates of return analyses
3- Farmer acceptability based on seasonal matrix ranking exercises.

Nevertheless, the 2000/2001 end-of-season survey of farmers who hosted trials and non-host farmers in neighbouring villages showed that farmers are adapting and adopting some technologies from the trial plots to their main fields (Table 14). The crop management practices being adopted/adapted by farmers in both Malawi and Zimbabwe are summarised in Table 11.

Table 14: Percentage of farmers reporting taking practices from trial plots to their main fields, 2000/2001

Taken practices from research to fields	Malawi		Zimbabwe	
	Host	Non-host	Host	Non-host
Yes	64.7	19.8	76.7	47.3
No	35.3	80.2	23.3	52.7

Malawi: n=227 (158 male, 69 female)
Zimbabwe: n=194 (138 male, 56 female)

Table 15: Farming practices taken up by farmers onto main fields from soil fertility research to their main fields, Malawi and Zimbabwe, 2000/2001

Crop management practices taken by farmers into main fields	% uptake Malawi (N=227)	Zimbabwe (N=194)
Groundnut varieties and groundnut rotation and intercrops	19	6.8
Maize-pigeon pea rotation and intercrop	16.7	0[1]
Maize-soybean rotation and intercrops	13.7	0
Maize-*Mucuna* rotation and intercrop	9.1	0.5
Incorporating crop residues	9.1	0.5
Spacing, planting methods	6.8	8.6
Maize hybrids	6.6	5
Maize-*Tephrosia* rotation and intercrop	6.1	0
Crop rotation	6.1	6.8
Compost manure	3	0.5
Early planting, top dressing with inorganic N, early weeding, many weedings, zero tillage, fermented cow dung	1.6	9.6
Kraal manure	1.5	2.3
New sorghum and pearl millet varieties	0[1]	17.3
Heaped covered manure	0	9.9
Dead level contours, infiltration pits	0	7.7
Seed priming	0	7.7
Pit manure	0	7.2
Modified tied ridges	0	5.4
Maize, sorghum and pearl millet-cowpea rotations and intercrops	0	4.1

[1]A zero responses indicate that the farmers had not been exposed to the crop management practice.

The adoption of maize-legume systems by households in both countries is influenced by access to input markets for seed and output markets to earn cash through commercial grain sale. In both countries the use of inorganic fertilizer is constrained by a combination of high fertilizer prices, and blanket recommendations that do not take account of households perceptions of risk and liquidity, as few households earn enough income from their crop sales to enable them to invest such large cash inputs. The small doses of fertilizer, 10 to 20 kg of N ha^{-1} that the project tested with farmers appears to be at an investment level that households are willing and able to risk. However, information is lacking on fertilizer application rates that farmers currently use, how they can best use the small quantities of fertilizer they have, and on manure-fertilizer combinations, and integrating inorganic and organic fertility amendments.

Table 15 shows that in both Malawi and Zimbabwe the most popular technologies were improved germplasm with accompanying management practices. However, the table also shows that farmers in Zimbabwe were much more willing to expand investments in a range of improved soil, water and nutrient management practices than in Malawi, where pre-plant ridges are the norm, rather than the exception. Other findings from the research showed, however, that adoption of soil, water and nutrient management practices should be accompanied by improvements in basic crop management practices such as variety selection, tillage, planting method, spacing, timing of planting and weeding in order for the investment in improved soil fertility management to provide acceptable payoffs.

In Malawi, it would appear from our survey data that proportionately more female-headed households have changed their crop management practices as a result of the projects activities. Female-headed households are adopting new maize varieties; groundnut, soybeans and *Tephrosia* intercrops; and modifying their plant populations to reflect those used in the trials (Table 10). In contrast, male-headed households were emphasising pigeon pea and *Mucuna* rotations, incorporation of plant residues, kraal and compost manures, and early planting and small quantities of fertilizer. These difference have been attributed to the fact that female-headed households tend to have greater land, labour and cash constraints, and as a consequence are more food deficit than male-headed households (Freeman, 2002).

Table 16: Practices taken up by farmers onto main fields by gender of household head, Malawi 2000/2001

Practice	Status of household heads		
	Male-Headed (n=158)	Female-Headed (n=69)	All (N=227)
New maize varieties	5.2	14.3	7.6
Groundnut rotation and intercrops	17.5	22.9	19
Soybean rotation and intercrops	12.3	17.1	13.7
Tephrosia rotation and intercrops	5.1	8.6	6.1
Pigeon pea rotation and intercrops	17.5	11.4	15.9
Mucuna rotation and intercrops	11.3	2.9	9.1
Incorporating crop residues	10.3	5.7	9.1
Crop rotations	7.2	2.9	6.1
Intercrops	0	2.9	0.8
Spacing, plant population	6.2	8.6	6.8
Early plant, small fertilizers	2	0	1.6
Kraal/compost manure	5.2	2.9	4.5

Focus group discussions held in both countries (Rusike and Twomlow, unpublished field notes, 2002; Ncube and Twomlow, 2001) showed that farmers' perceptions of soil fertility management vary widely, depending on the resources available to the individual household. In Zimbabwe, *de facto* female-headed households with access to cash appeared to be adopting new cereal varieties, seed priming, pit-composted manure and small quantities of inorganic fertilizer, manure and weeding combinations (Table 11). In contrast, the poorer resourced *de jure* female-headed households were adopting heap-covered composted manure, dead level contours, modified-tied ridges and reduced tillage because they have more severe capital and labour constraints. Male-headed households with access to labour and draught animals but not cash favoured legume rotations, small doses of fertilizer and water harvesting, especially infiltration pits that are labour-intensive.

Table 17: Practices taken up by farmers onto main fields by gender of household head, Zimbabwe, 2000/2001

	% uptake			
Practice	Male-Headed (n=138)	*De facto* Female (n= 42)	*De jure* Female (n= 14)	All N=194)
New cereal varieties	31.5	37.8	16.6	32.3
Legumes rotations/intercrops	20.8	10.2	13.3	18.7
Seed priming, planting methods, spacing	16.1	20.5	16.6	16.8
Small fertilizer/weeding/manure	8.6	13.8	0	7.7
Treated manure	16.7	30.9	26.7	19.9
Water harvesting	14.8	0	20	13.6
Reduced tillage/compost	0.6	0	6.6	1.4

Solutions from the whole farm mathematical programming model suggest that for male, *de facto* and *de jure* headed households that the most attractive technologies are:
Legume-rotations and treated manures for male-headed households with access to draft animals, labour and land;
Small quantities of inorganic fertilizer, treated manure and manure-fertilizer technologies for *de facto* female-head households with an off-farm cash income;
Legume intercrops in the female-headed households, typically *de jure*, who have the most severe resource constraints.

The model outputs disagreed with the working hypotheses based on expert opinion, and show that the wealthiest households, irrespective of gender, with lowest opportunity cost of working capital, will allocate more land and money to inorganic fertilizers than the more marginalised groups. These marginalised groups typically have less working capital and a higher opportunity cost. Therefore, better-resourced households will invest in high input technologies such as small quantities of fertilizer and treated manure. In contrast, the poorer resourced households will invest in low input technologies such as legume-cereal intercrops, as their opportunity cost of labour is very high and they are better off selling labour to wealthier households.

Conclusions and Lessons Learned

Overall, three major lessons have been learned about the differential adoption and targeting of alternative soil water and nutrient management to differently resourced households:

1. Small quantities of fertilizer and manure-fertilizer combinations have a high payoff and supplying inorganic fertilizers in small packs reduces the liquidity constraint and enhances returns to investment in chemical fertilizers.
2. Input and output markets drive legume intensification.
3. Legume intensification needs to target poor households for food for home consumption and wealthier households for cash income through producing marketable surpluses.

Another conclusion is that a pure farmer-led approach may not always be appropriate where researchers have spent time understanding the farming system and the externalities that impact upon it, simulation playing an important part in this understanding. A major advantage of linking FPR and simulation modeling was the co-learning that took place between the researchers and the farmers about the impacts of climatic risk and resource endowments, and how they influence household's investment choices. In fact, if Integrated Natural Resource Management (INRM) research is about better communication and more effective interaction on the part of researchers with managers (about system management), then linking simulation modeling and participatory research should be viewed as an integral part of applied INRM in smallholder farming systems. The results also indicated that when there are no clear procedures to directly target women farmers, and gender issues are not sufficiently integrated into the research process they tend to be under-represented.

Synthesis and Conclusions

M&E to aid impact facilitation

The case studies show clearly that rural technology change, brought about by the generation and diffusion of new technologies, is an evolutionary and highly complex process. An evolutionary process is one in which novelties are generated, selections of beneficial novelties are made and these improvements are retained and promulgated (Douthwaite et al. 2002). The Uganda and Nigeria case studies show that farmers were actively modifying the technologies in ways that improved their 'fitness' or adoptability. In Uganda farmers sought alternative uses for the LCC and BT technologies that would increase the return on their investment in labour and land. In Nigeria, farmers sought to find compromises between the 'best bet' agronomic practice and what fitted their own systems. Some of these innovations have been incorporated in the recommended package for Integrated *Striga* Control. The Zimbabwe and Malawi case study showed how important these compromises are because farmers do not select technologies purely on agronomic or economic performance, which is often the basis by which researchers select their 'best-bets' for their trials (see Figure 1). Instead farmers chose to adopt based on a number of factors that is dependent on the resources available to that household, perceptions of risk and the gender of the household head. The Uganda case study showed that preferences for technologies changes from location to location. Hence, identifying farmer adaptations through M&E is an important source of incremental improvements to a technology and future research areas, as well as providing good insights into farmers' perceptions and motivations.

The case studies show that M&E also has a crucial role to play in identifying differences in perceptions between researchers and farmers, and between individual farmers in their responses to new ideas and technologies. In all three case studies it was impossible for researchers to know beforehand how different farmers would react to the new technologies. However, the M&E carried out gave this information and has allowed the projects to adjust accordingly, thus making widespread adoption and impact more likely. For example, the M&E exercise helped ICRISAT and its partners to see that *de jure* women-headed households can generally only adopt the lowest input technology, which was the legume-cereal intercrops because they did not have the cash to buy inorganic fertilizer, or the labour to make and spread compost. In Nigeria, M&E findings showed that many farmers were adopting improved germplasm but not the concepts of sole cropping and crop rotation, preferring instead to continue with their own mixed cropping practices. In response the project will carry out participatory partial budgeting to examine together with farmer the advantages and disadvantages of sole versus mixed cropping.

The three case studies largely confirm the conceptual map of the development and adoption process adopted in the case studies shown in Figure 1. All the case studies found that there is a role for researchers to take the lead in introducing 'best bets'. Those 'best-bets' are more likely to adopted and adapted by farmers when researchers have spent time understanding local farming systems, and, in the case of Zimbabwe and Malawi used simulation modelling to evaluate different options with farmers. Purely farmer-led participatory technology development is less likely to bring new ideas into to community because researchers have a deeper knowledge and understanding of new technical options, while farmers are concerned with their current problems and have little human and financial resources to search for and adapt novel solutions. However, whatever the source of innovation, once adoption begins, M&E has a role to play in facilitating the close interaction between farmers and researchers required to co-develop new technologies to make them more widely adoptable.

The Zimbabwe/Malawi and Nigerian case studies looked at farmer to farmer spread of new technologies and ideas, in other words the selection and promulgation functions of the evolutionary innovation process. Whether farmers recommend a new technology to others, and who they recommend to, are the most important indicators of whether a technology is likely to scale-out, where it will go, and how fast. The Nigerian case study is using a GIS-based approach to map the adoption/adaptation, selection and promulgation process and is developing an extension approach that complements existing promulgation channels.

M&E as a basis for Priority Setting and ex post Impact Assessment

Thomas Kuby has developed an impact model, shown in Figure 8, based on experience at GTZ (Kuby, 2000). The model shows projects carrying out their own M&E, similar to ways in which M&E has been carried out in the three case studies, to the point of assessing whether the project has delivered intended benefits, or unintended benefits and negative consequences. Assigning this role to the project comes from years of project experience that has shown that: "as a rule, self-evaluation is more critical and better value for money than external monitoring – and that it makes a much greater contribution to learning, both in the projects and in the whole organisation"[6] (Kuby, 2000 p. 4). This learning helps make impact more likely, as well as contributing to priority setting in the organisation.

Priority Setting

Formal and static routines are not adequate for research priority setting due to the essential unpredictability of complex systems. Since many outcomes cannot be forecast, expected impacts cannot guide priority setting. Even though particular outcomes cannot be predicted, it is possible to identify factors that will, with high probability, affect the chances of success or failure. More flexible approaches (such as adaptive management) require strong M&E to identify as early as possible unintended (both positive and negative) consequences so that appropriate responses can be implemented. M&E also has a role to play to ensure that all stakeholders understand the processes that generated the outcomes.

In addition to contributing to organisational learning, M&E can help all partners, from farmers to donors, to learn from the research to adoption process. The three case studies presented here showed that farmer adoption and subsequent innovation and adaptation are invaluable indicators of the likely adoptability of the introduced options. Early identification of farmer adoption / non adoption and modification allows the research process to be adapted and allows the setting of new priority areas for research. Without this flexibility in the approach, 'best bet' options demonstrated on-farm are unlikely to undergo the necessary co-development necessary to be more widely adopted.

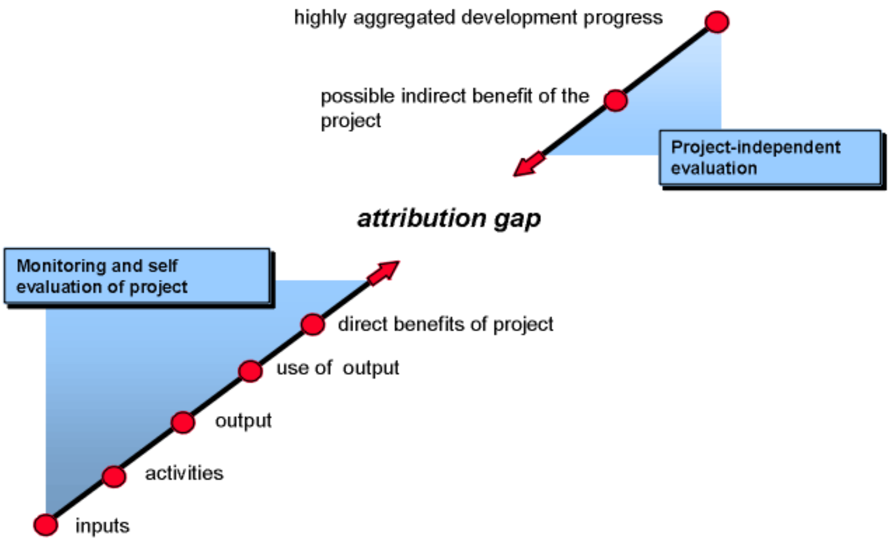
***Ex post* impact assessment**

The Kuby model shows an attribution gap between a project's direct benefits and wider, more highly aggregated impacts, for example poverty alleviation, that might result from these benefits. Hence the model agrees with our earlier discussion of why attribution of impact is nearly always impossible because of the interconnected nature of causes and effects.

The causes and effects that lead from a project's direct benefits to broader impacts result from two linked processes that are known as scaling-out and scaling-up. Scaling-out is a horizontal spread of an innovation from farmer to farmer, community to community, within the same stakeholder groups. Scaling-up is an institutional expansion from grassroots organizations to policy makers, donors, development institutions, and other stakeholders key to building an enabling environment for change. Both are linked because as a change spreads further geographically the greater the chances of influencing those at higher levels, and likewise, as one goes to higher institutional levels then the greater the chances for horizontal spread.

[6] Kuby, T. 2000. Turning attention towards results: how GTZ is building its impact evaluation capacity. Internal GTZ document. Eschborn, Germany.

Figure 8: Kuby's impact model (Kuby, 2000)



The three case studies help show why an attribution gap exists. The case studies demonstrate that even to achieve direct benefits, the projects have been working with a wide range of agents, including farmers, NGOs, extension workers and national research institutes in an iterative and adaptive process. Attributing impact even at this stage to individual agents is impossible. Scaling-out and scaling-up will require a broadening of the process and more agents to become involved, particularly those at a higher scale (e.g., state and national level).

Even though attributing impact to individual stakeholders may be impossible, this does not mean ex post impact assessment should not be carried out. *Ex-post* IA is important for organisational learning and change, and the adaptive management of complex systems. Also *ex-post* IA remains necessary to help donors demonstrate to their constituency that the money they have given out has contributed to development. Hence, rather than attempt to quantify impact using 'heroic' assumptions, *ex-post* impact assessment should focus on establishing what development changes have taken place, and whether the project as a whole made a contribution. In other words, more than concentrating the efforts in a few impact indicators (e.g., rate of return or output growth) of dubious meaning, IA should focus on a) the processes of knowledge generation and diffusion, b) the creation of organizational capabilities, i.e., the collective ability to develop appropriate solutions to identified problems and c) the emergence and evolution of innovation networks.

The GTZ-led donor Workgroup on Assessing the Impact of Agricultural Research in Development recently published a set of requirements for plausible impact assessment (Bauer et al., 2002) that are consistent with this view of ex post impact assessment. The donor workgroup say that plausible impact assessment should:

- Identify the source of impact being assessed;
- Clearly state the impact model used by the impact assessor;
- Identify the 'theory of action' (i.e., the impact pathway) of the project being assessed;
- Discuss the objectives and limitations of the impact assessment;
- Specify and test impact hypotheses;
- Consider alternative causes of impact;
- Consult a range of informed opinions.

The workgroup does not say that impact should be attributed or quantified.

The Nigerian case study shows how M&E based on an impact pathway can form the foundation of a plausible *ex post* impact assessment by making explicit the source of impact (the project's direct outputs), the impact model, the impact pathway and the impact hypotheses. The impact pathway evolves during the duration of the project as M&E identifies incipient scaling out and up processes including processes of knowledge generation and diffusion, the emergence and evolution of innovation networks, and the creation of organisational capabilities. Hence, the description of the impact pathway at the end of the project would be an invaluable starting point to *ex-post* impact assessment some years after. Indeed, without process M&E, plausible *ex-post* IA of INRM projects, based as it needs to be on a convincing explanation of process, will be extremely difficult.

Institutionalising M&E in CG Centres

The M&E approaches described in the three case studies are relatively new and are not yet well institutionalised in their respective CGIAR Centres. Whether they are or not will depend on three factors:

- Being able to demonstrate to fellow researchers that the benefits of M&E are worth the cost;
- Having the capacity to carry out effective M&E;
- Support for M&E from senior management.

Of course, all three are linked. If CGIAR scientists can come to see M&E as something useful and not threatening then support from senior management is likely to follow, together with additional capacity to carry out the work. Experience shows that self-monitoring is less threatening and more useful than external M&E, which suggests that individual projects within Centres should be responsible for M&E, but with backstopping from an M&E unit.

References

Alston, J.M., G.W. Norton and P.G. Pardey. 1995. Science under Scarcity. Cornell University Press, New York, USA.

Bauer, H., M. Bosch, S. Krall, T. Kuby, A. Lobb Rabe, P.T. Schultz, A. Springer-Heinze. 2002. Establishing Plausibility in Impact Assessment. The Working Group on Assessing the Impact of Agricultural Research on Development. Paper presented at the International Conference on the Impacts of Research and Development, San José, Costa Rica 4-8 February 2002

Dimes, J., Muza, L., Malunga,G. and Snapp,S., 2002 Trade-offs between investments in nitrogen and weeding: On-farm experimentation and simulation analysis in Malawi and Zimbabwe. 7th Eastern and Southern Africa Regional Maize Conference and Symposium on low-Nitrogen and Drought Tolerant – Tolerant Maize Nairobi, Kenya, 11-15th February, 2002 Nairobi, Kenya, 11-15th February, 2002. In press.

CIFOR, 1999. Integrated Natural Resource Management – the Bilderberg Consensus. Downloaded from http://www.inrm.cgiar.org/documents/bb_meeting.htm

Dimes, J., Muza, L., Malunga,G. and Snapp,S., 2002 Trade-offs between investments in nitrogen and weeding: On-farm experimentation and simulation analysis in Malawi and Zimbabwe. 7th Eastern and Southern Africa Regional Maize Conference and Symposium on low-Nitrogen and Drought Tolerant – Tolerant Maize Nairobi, Kenya, 11-15th February, 2002 Nairobi, Kenya, 11-15th February, 2002. In press.

Douthwaite, B., N. C. de Haan, V. Manyong, and D. Keatinge. 2001. Blending "hard" and "soft" science: the "follow-the-technology" approach to catalyzing and evaluating technology change. Conservation Ecology 5(2): 13. [online] URL: http://www.consecol.org/vol5/iss2/art13

Douthwaite, B. 2002. Enabling Innovation: A Practical Guide to Understanding and Fostering Technological Change. Zed Books, London, England.

Douthwaite, B. J.D.H. Keatinge and J.R. Park. 2002. Evolutionary learning selection: A model for planning, implementing and evaluating participatory technology development. Agricultural Systems 72 (2) 109-131.

Ekboir, J. 2002. Why impact analysis should not be used for research evaluation and what the alternatives are. Paper presented at the International Conference on the Impacts of Research and Development, San José, Costa Rica 4-8 February 2002

Ekboir, J. and Parellada, G. 2002. Public-Private Interactions and Technology Policy in Zero-Tillage Innovation Processes - Argentina, in Byerlee, D. and Echeverría, R. (eds.), *Agricultural Research Policy in an Era of Privatization: Experiences From the Developing World. Oxon: CABI.*

Environmental Systems Research Institute (ESRI). 1999. ArcView GIS. 380 New York St. Redlands, California, USA.

Freeman, H.A., 2002. Comparison of farmer-participatory research methodologies: case studies in Malawi and Zimbabwe. Working paper series 10. PO Box 39063, Nairobi: Socioeconomics and Policy Program, International Crops Research Institute for the Semi-Arid Tropics. 28pp.

Horton, D. 1997. Disciplinary roots and branches of evaluation: some lessons for agricultural research. ISNAR Discussion Paper 96-7. International Service for National Agricultural Research (ISNAR), The Hague, The Netherlands.

Horton, D. and G. Prain. 1989. Beyond FSR: new challenges for social scientists in R&D. *Quarterly Journal of International Agriculture.* 28, December

Kuby, T. 2000. Turning attention towards results: how GTZ is building its impact evaluation capacity. Internal GTZ document. Eschborn, Germany.

Murwira H.K. and T.L.Kudya. In press. Economics of heap and pit storage of cattle manure. Tropical Science.

Ncube, B And Twomlow, S. 2001. Soil fertility management – integrating farmers and researchers priorities . Proceedings of a Planning workshop , 18-19 September 2000, Masvingo, Zimbabwe. ICRISAT Bulawayo, Zimbabwe. PO Box 776, Bulawayo, Zimbabwe: International Crops Research Institute for the Semi-Arid Tropics and CIMMYT – Zimbabwe, PO Box MP 163, Mt Pleasant, Harare, Zimbabwe: Centro Internacional de Mejoramiento de Maiz y Trigo. 32 pp.

Nyende, P., and Delve, R.J. Farmer participatory evaluation of legume cover crop and biomass transfer technologies for soil fertility improvement using farmer criteria, preference ranking and logit regression analysis in eastern Uganda. Submitted to Nutrient Cycling in Agroecosystems

Riches, C. R., Twomlow, S. J. and Dhliwayo, H. H., 1997. Low-input weed management and conservation tillage in semi-arid Zimbabwe. Experimental Agriculture. 33: 173-187.

Sauerborn, J. 1991. The economic importance of phytoparasites *Orobranche* and *Striga*. In J.K. Ransom, L.J. Musselman, A.D. Wosham and C. Parker (eds). Proceedings of the 5th International Symposium on Parasitic Weeds, 24-30 June 1991, pp, 137-143. International Maize and Wheat Improvement Center (CIMMYT), Nairobi, Kenya.

Sayer J. and B. Campbell. 2001. Integrated natural resource management research to integrate productivity enhancement, environmental protection and human development. Conservation Ecology 5(2)

Schulz, S., M.A. Hussaini, J. Kling, D.K. Berner and F.O. Ikie. in press. Evaluation of integrated Striga hermonthica control technologies under farmer management. Journal of Agronomy and Crop Science.

Scoones, I. 1998. Sustainable rural livelihoods: a framework for analysis. IDS Working Paper 72. University of Sussex, Brighton, England.

Twomlow, S.J., And Ncube, B., 2001. Improving soil management options for women farmers in Malawi and Zimbabwe: proceedings of a Collaborators Workshop on the DFID-supported project 'Will Women Farmers Invest in Improving their Soil Fertility Management? Experimentation in a risky environment. 13-15 September 2000, ICRISAT Bulawayo, Zimbabwe. PO Box 776, Bulawayo, Zimbabwe: International Crops Research Institute for the Semi-Arid Tropics. 150 pp.

Twomlow, S.J., Rusike, J. And Snapp, S. S., 2002. Biophysical Or Economic Performance – Which Reflects Farmer Choice Of Legume 'Best Bets' In Malawi. 7th Eastern and Southern Africa Regional Maize Conference and Symposium on low-Nitrogen and Drought Tolerant – Tolerant Maize Nairobi, Kenya, 11-15th February, 2002 Nairobi, Kenya, 11-15th February, 2002 In press

Agronomie (in Press)

Organic resource management in sub-Saharan Africa: validation of a residue quality-driven decision support system

Bernard Vanlauwe[1], Cheryl A Palm[1], Herbert K Murwira[1] and Roel Merckx[2]
[1]Tropical Soil Biology and Fertility Programme, UN Gigiri, PO Box 30592, Nairobi, Kenya
[2]Laboratory of Soil Fertility and Soil Biology, Faculty of Agricultural and Applied Biological Sciences, Kasteelpark Arenberg 20, 3001 Heverlee, Belgium

Keywords: farmyard manure, fertilizer, organic-mineral interactions, Organic Resource Database, percentage fertilizer equivalency values, plant materials, residual effects

Abstract
A conceptual Decision Support System (DSS) for organic N management was developed based on information on residue quality – N-mineralization relationships. The current paper aims at validating the DSS using data obtained in sub-Saharan Africa on biomass transfer systems with maize. The percentage fertilizer equivalency (%FE) values of the organic resources increased linearly with their N content above a minimum of 2.3% N. For resources with high polyphenol contents, the slope of the regression decreased and the critical N content increased to 2.8%. For manures, no clear relationship between their %FE and quality was observed. Medium quality materials are to be applied together with mineral N. Several cases are discussed in which added benefits as a result of positive interactions between medium quality organic resources and mineral N were generated. Finally, thought is given on the information needed to turn the DSS from a concept into a useful soil management tool.

2. Introduction
For ages, agricultural production depended on organic resources for soil fertility replenishment, either by including long-term fallow periods, as was, e.g., the case in sub-Saharan Africa (SSA), or by application of vast amounts of manures or other organic resources, e.g. sods of peat in northern Belgium (Dudal, 2001). The use of fertilizers started in western Europe only at the end of the 19th century in response to a higher demand for food. Other continents followed at a later stage, but even up to the mid-1960s, fertilizer use in SSA was restricted to export crops such as groundnut, cotton, coffee, tobacco, or oil palm (Dudal, 2001).

During the 'Green Revolution' in the 1960s in Asia and Latin America organic resources were not considered essential in boosting agricultural production. In this context, Sanchez (1976) stated that when mechanization is feasible and fertilizers are available at reasonable cost, there is no reason to consider the maintenance of soil organic matter (SOM) as a major management goal. However, application of the 'Green Revolution' strategy in SSA resulted only in minor achievements because of a variety of reasons (IITA, 1992). This, together with environmental degradation resulting from the massive applications of fertilizers and pesticides and the abolition of the fertilizer subsidies in SSA, imposed by structural adjustment programs led to a renewed interest in organic resources in the early 1980s (Table 1). This interest has only grown stronger in recent years driven by the development of an Integrated Soil Fertility Management (ISFM) strategy for soil fertility replenishment of which the combined application of organic resources and mineral inputs forms the technical backbone. In this context, Sanchez (1994) revised his earlier statement by formulating the Second Paradigm for tropical soil fertility research: 'Rely more on biological processes by adapting germplasm to adverse soil conditions, enhancing soil biological activity and optimizing nutrient cycling to minimize external inputs and maximize the efficiency of their use'.

Since the early 1980s, progress in developing organic resource management related knowledge has been substantial, driven by the hypotheses formulated by Swift et al. (1979) and Swift (1984, 1985, 1986), culminating in an International Symposium in 1995 (Table 1). As a result of the Symposium, efforts were made to consolidate information on residue quality – N dynamics relationships resulting in an Organic Resource Database (ORD). The ORD contains information on organic resource quality parameters and N mineralization dynamics from almost 300 species found in tropical agroecosystems (Palm et al., 2001). A careful analysis of the information in the ORD has led to the development of a Decision Support System (DSS) for organic matter (OM) management (Fig. 1) (Palm et al., 2001). The DSS makes recommendations for appropriate use of organic materials, based on their N, polyphenol, and lignin contents resulting in four classes of organic resources (Palm et al., 2001). For instance, high quality organic resources with a N content > 2.5%, a lignin content of < 15% and a polyphenol content of < 4% are recommended to be applied directly to the soil as these are expected to release a substantial part of their N in the short term (Fig. 1). Medium quality organic residues having < 2.5% N and < 15% lignin, or > 2.5%N and a polyphenol content > 4%, on the other hand, are recommended to be applied together with fertilizer N or high quality organic resources. Lastly, low quality organic resources with a low N and high lignin content are recommended to be surface applied as such residues would result in the most substantial mulch effects. The combined application of organic resources and mineral N is hypothesized to yield added benefits in terms of extra yield or improved soil fertility compared with the sum of the responses in the treatments with sole application of organic resources and mineral N. A *Direct* and *Indirect Hypothesis* which could form the basis for the occurrence of such benefits has been formulated by Vanlauwe et al. (2001). The *Direct Hypothesis* was formulated as: *Temporary immobilization of applied fertilizer N may improve the synchrony between the supply of and demand for N and reduce losses to the environment*. The *Indirect Hypothesis* was formulated for N supplied as fertilizer as: *Any organic matter-related improvement in soil conditions affecting plant growth (except N) may lead to better plant growth and consequently enhanced efficiency of the applied N*. Both hypotheses, when proven, lead to an enhancement in N use efficiency, processes following the *Direct Hypothesis* through improvement of the N supply and processes following the *Indirect Hypothesis* through an increase in the demand for N. Obviously, mechanisms supporting both hypotheses may occur simultaneously.

The objectives of the current paper are (i) to validate the concepts proposed in the DSS with field data, including plant materials and animal manure as organic resources; (ii) to explore the occurrence of added benefits when applying organic resources in combination with mineral N, and (iii) to reflect on the activities required to develop the DSS into a practical recommendation tool.

3. Experimental Approaches

3.1. Experiments in West, East and southern Africa studying the N supply potential of organic resources

A greenhouse trial was carried out in Ibadan, southwestern Nigeria, aiming at quantifying immediate and residual relationships between organic resource quality and maize N uptake (Vanlauwe et al., unpublished data). A range of organic materials containing between 0.14 and 3.53% N was applied in pots with a Nitisol from Southern Benin Republic at an equivalent rate of 90 kg N ha^{-1} and maize was grown for 7 weeks. After harvesting the first crop, a second crop was grown for another 7 weeks without fresh residue application. Total N uptake by the maize in the shoots and roots was measured at each harvest.

In East and southern Africa, a set of field experiments was set up to determine the fertilizer equivalency values of organic resources (Murwira et al., 2001). Each trial contained a set of locally available sources of plant materials or cattle manure. The organic resources were applied on the field in a randomised complete block design which included a number of plots aimed at determining the response to fertilizer N using maize as a test crop. Based on the response curve and the yield increases in the organic resource treatments, fertilizer equivalency values were calculated and converted to percentage fertilizer equivalency values (%FE) taking into account the N application rates of the organic materials.

In West Africa, a multilocational set of field experiments also using maize as a test crop was established using various inputs of plant materials – and cattle manure in a single case – and the %FE was calculated using the similar approach as indicated above (Vanlauwe et al., 2002). In both sets of trials, P and K were applied in non-limiting quantities to ensure that N was the sole nutrient limiting maize production.

3.2. Evaluation and quantification of added benefits in experiments with simultaneous application of organic resources and mineral N in West, East and southern Africa

Several trials were established in the various sub-regions aiming at quantifying potential added benefits in treatments with combined applications of organic resources and mineral N (Table 2). All cropping systems considered were organic resource transfer or biomass transfer systems using maize as a test crop. Added benefits were mathematically evaluated using the equation:

$$AB = Y_{comb} - (Y_{fert} - Y_{con}) - (Y_{OM} - Y_{con}) - Y_{con} \qquad (1)$$

where *AB* signifies *Added Benefits* and Y_{con}, Y_{fert}, Y_{OM}, *and* Y_{comb} mean grain yields in the control treatment, in the treatments with sole application of fertilizer and organic matter, and in the treatment receiving both inputs, respectively (Vanlauwe et al., 2001). In equation 1, the yields are adjusted for similar amounts of organic resources and mineral N applied in the combined as in the sole treatments, following information obtained through the N response curve or if the latter is absent assuming linear responses to applied organic and mineral N.

4. Evidence from field trials in West, East and southern Africa

4.1. Agronomic evaluation of organic resources of varying quality as source of N

The greenhouse trial data clearly show a significant positive relationship between the organic resource N content and the total maize N uptake of the first crop (Fig. 2). Low quality materials such as maize stover or sawdust immobilized N resulting in less N uptake compared to the unamended control. For the second crop, however, the relationship was negative, indicating that the medium to low quality materials provide more N to a second growing maize crop compared to the high quality materials (Fig. 2). Even in the treatment with maize stover, no further immobilization of N was observed. Only the sawdust treatment kept the N immobilized beyond the second crop. These data show that while organic resources with a high amount of available N can immediately stimulate crop growth, while for medium to low quality materials, residual N supplies are greater. More cropping cycles would be needed to judge whether the cumulative yields are similar for the high and low N organic resources. Cadisch et al. (1998), on the other hand, observed no compensation in initial N release from low quality, high polyphenol containing prunings at later harvests compared to high quality materials and attributed this to the stability of polyphenol-N complexes. The data also indicate that for materials with a N content below 1%, additional N should be applied either as fertilizer or as high quality organic matter to overcome the negative impacts caused by N immobilization.

Data from the field experiments in West, East and southern Africa show that the percentage fertilizer equivalencies (%FE) values for organic materials with a low polyphenol content (< 4%) and a N content > 2.3% were positively related to their N content (Fig. 3). The critical level of N for increasing crop yield was 2.3%, confirming the initial value hypothesized by Palm et al. (2001). Organic matter with a high polyphenol content (> 4%) still led to positive %FE values, but the increase with increased N content was less and the N content needed to improve maize yield was 2.8 rather than 2.3% (Fig. 3). Polyphenol – N interactions seem to delay the immediate availability of N as concluded by others from data obtained under controlled laboratory or greenhouse conditions (Palm and Sanchez, 1991, Oglesby and Fownes, 1992). Data obtained with *Calliandra calothyrsus* residues did not show a consistent trend. While in all cases their polyphenol content was high, data from certain sites did not show any reduction in %FE. This may be related to the specific rainfall patterns, as high rainfall immediately after applying the *Calliandra* residues may remove a substantial part of the polyphenols through leaching. While from the current data polyphenols appeared to be under certain conditions important modifiers guiding initial N release from organic materials, the lignin content was not observed to improve on the derived equations. This does, however, not exclude their importance in medium to long term N dynamics, as shown in the greenhouse experiment (Fig. 1) and discussed below.

Some organic resources led to N fertilizer equivalency values exceeding 100%, especially in the case of *Tithonia diversifolia* (Fig. 3). This is likely caused by a better synchrony between the supply of and demand for N derived from *Tithonia* residues than for immediately available fertilizer-derived N. Mineral N inputs are readily available and as such prone to leaching and/or gaseous losses, even if split applied.

Manure does not show a consistent trend across sites (Fig. 3). Very low N containing cattle manure was observed to decrease crop yield but fertilizer equivalency values of manure containing between 0.7 and 2.4% N were almost similar and equal to about 35%. N content alone could not satisfactorily explain the observed responses to manure application indicating that other indicators are necessary for quantitative evaluation of manure. This may be related to changes in quality and partial stabilization of the organic resources while passing through the rumen or while storing pending application on the field. Nzuma and Murwira (2000) showed considerable differences in manure quality when stored in a pit or heap. Manure may require other indicators for assessing its quality, likely based on nutrient and biochemical components the soluble fraction rather than on the overall material.

4.2. Occurrence and quantification of added benefits

Organic resources with a N content below 2.5% would need to be applied in combination with additional mineral N to substantially increase crop yields (Fig. 3). Significant added benefits in treatments with combined application of organic resources and mineral N do occur in various experiments although the mechanisms governing these benefits are not always clearly understood. In the experiment in Zimbabwe with various mixtures of cattle manure and ammonium nitrate, added benefits ranging between 663 and 1188 kg maize grains ha^{-1} were observed by Nhamo (2001), as calculated using equation 1 (Fig. 4). The author related this to the supply of cations, contained in the manure, which may have alleviated constraints to crop growth caused by the low cation content (CEC varied between 1.2 and 2.5 $cmol_c\ kg^{-1}$ with an average of 1.7 $cmol_c\ kg^{-1}$) of the very sandy sites (clay content varied between 2 and 10% with an average of 4%). Although temporary immobilization of fertilizer N by decomposing manure can not be excluded, this may be less likely as the C/N content of the used manure was below 10, assuming that this would be a suitable indicator for assessing N dynamics of manure. In a trial in central Kenya, Okalebo et al. (2002) similary observed added benefits of 684 kg grains ha^{-1} in 1998 when mixing low quality wheat straw and soybean trash with urea for an acidic Ferralsol (pH-water of 4.9) (Fig. 5). After application of the organic residues, the pH-water increased to 5.4, on average, while pH in the control soils remained unchanged. Rainfall in 1997 was low and not well distributed leading to absence of major responses to applied N.

Mucheru et al. (2002) observed added benefits ranging from – 250 to + 550 kg maize grains ha^{-1} during the short rainy season of 2000 (Fig. 6). Values for the long rainy season, which experienced lack of rainfall after germination, were not different from 0. These benefits varied substantially for the different organic resources used. The high amount of K in the *Tithonia* residues may have caused the substantial added benefits in the combined *Tithonia*-N fertilizer treatment, as earlier observed by Sanchez and Jama (2001). Besides supplying K, Tithonia residues have been shown to ameliorate soil aggregation, reduce P sorption sites, reduce P-metal complexes and Al-toxicity (Cong, 2000). Causes for the added benefits created in the cattle manure treatment are not clear.

While in the above experiments, added benefits were observed only for certain organic resources, in the Sekou experiment, in which organic resources with a N content varying between 2.4 and 4.7% were used, similar added benefits were observed for all organic resources (Fig. 7). As the site experienced drought stress during maize grain filling, Vanlauwe et al. (2002) attributed the added benefits to improved soil water conditions in the mixed treatments, caused by the surface or sub-surface placement of the organic resources, compared to the treatment with sole application of fertilizer. Alleviation of moisture stress may have improved the N use efficiency of the applied fertilizer. In formerly discussed trials with organic resources, no alleviation of moisture stress was observed (Figs. 5 and 6) but in these trials, organic resources were incorporated. During seasons with shortage of rain, this residue management practice has been shown not to substantially alter soil moisture conditions vis-à-vis surface or subsurface placement (Minhas and Gill, 1985, Sembiring et al., 1995). No soil water data were taken, so the above would need to be evidenced.

5. Looking ahead

The final product of all above work should be a tool to assist farmers on how to optimally manage their scarcely available organic resources and costly mineral fertilizers, preferably adapted to their biophysical environment and targeted yields for specific crops. Although this seems like an impossible task, generation of the following information would signify substantial progress: (i) generation of a more detailed understanding of the mechanisms creating added benefits, (ii) assessment of the influence of intrinsic soil properties (e.g., texture and clay mineralogy, water holding capacity), and climate conditions (e.g., risk of rain shortage) on the latter, (iii) quantification of the residual effects of organic resources of varying quality, applied sole or in combination with fertilizer, on crop yield, and (iv) evaluation of the immediate and residual responses of other crops besides maize to applied organic resources and fertilizer.

The mechanistic basis for added benefits created through positive interactions between OM and mineral N is broad and has not been clearly understood yet. Although in the above case studies, likely reasons behind the added benefits could be put forward, little or no evidence was gathered to substantiate these. Trials which explicitly quantify some of the changes in soil properties as affected by OM application are needed. Such trials would also include treatments in which the hypothesized constraint to crop growth is alleviated using external inputs containing only the agent addressing this constraint. Although it may be an illusion to aim at understanding all interactions between organic resources and fertilizer under all conditions, under certain specific conditions, clear organic resource-related improvements in soil fertility status could be identified. For instance, the use of high P containing manure or compost on low P soil could lead to an improved use efficiency of N fertilizer and consequently added benefits. When looking at legume-cereal rotations, the mechanisms potentially creating added benefits may even be more diverse relative to the ones discussed in biomass transfer systems in this paper. Many rotational effects are often explained in terms of changes in pest and disease spectra during legume growth (Akhtar, 2000) or in terms of legume rhizosphere processes (Vanlauwe et al., 2000).

Organic resources are known to show some residual effects. Optimal nutrient management strategies need to take into account these effects. In the long term, an improved soil organic matter status may equally lead to enhance N fertilizer use efficiencies, although quantifying the latter may prove very difficult. Vanlauwe et al. (unpublished data), e.g., showed a negative relationship between the proportion of maize N derived from urea and the soil total N content, presumably caused by a higher supply of native soil N in soils with a higher total N content.

Most of the data presented in this paper, and similarly in other work dealing with soil fertility management, were obtained in maize-based cropping systems. It is likely, however, that farmers would prefer to use their often scarcely available organic resources on crops which yield more income. In this context, it has been observed that farmers in western Kenya would rather apply high quality *Tithonia* residues to kale (*Brassica oleracea*) rather than maize (Jama, personal communication). This would not necessitate to initiate a vast amount of trials using other crops than maize, but to consider the nutrient uptake patterns of those other crops and use the information obtained for maize to test specific hypotheses related to the potential effects of organic resources and fertilizer on other crops.

After having obtained relevant information as described above, two extra steps may be required to complete the development of a user-friendly decision aid: (i) all above information needs to be synthesized in a quantitative framework and (ii) that framework needs to be translated in a format accessible to the end-users. The quantitative framework could look as presented in Fig. 8 for a situation where all interactions between organic matter and fertilizer happen through N immobilization reactions, thus supporting the *Direct Hypothesis*. Temporary immobilization of fertilizer N by medium to low quality resources may reduce the potential for losses of fertilizer N materials and consequently less fertilizer N may be required to reach the same amount of available N (the 'added benefits' situation in Fig. 8). If the immobilization lasts beyond a growing season, on the other hand, additional fertilizer N may be required to reach the same amount of available N (the 'immobilization' situation in Fig. 8). The current concept may be adapted to initial soil fertility status by including a background soil N supply and to different crops. In case the mechanisms creating added benefits following the *Indirect Hypothesis* are known, the concept could also be adapted to these conditions. The final format of the decision aid should take into account the realities on the field. Some of these realities, among others, are: (i) large scale soil analyses are not feasible, so local soil quality indicators need to be included in decision aids as farmers use those to appreciate existing soil fertility gradients within a farm; (ii) conditions within farms vary as does the availability of organic resources and fertilizer, therefore rules of thumb rather than detailed quantitative recommendations would be more useful to convey the message to farmers; (iii) farmers decision making processes involve more than just soil and crop management; and (iv) access to computers, software and even electricity is limited necessitating hard copy-based products.

6. Conclusions

Although the data obtained largely support the concepts outlined in the DSS for organic N management, the reality on the field is such that the availability of high quality, fertilizer-like organic materials is very limited. Therefore, the arms dealing with medium to low quality organic resources are likely to be most relevant for real cropping systems. Such organic resources are recommended to be applied in combination with mineral fertilizer, and when doing so, added benefits do occur, although their mechanistic basis if most of the time not clearly understood. The relevance of such potential added benefits needs to be assessed for various biophysical environments and crops. In conditions where it is difficult to assess these potential benefits, assuming additive effects is usually good enough as a first approach as negative interactions are not commonly observed. Finally, generation of the needed knowledge will by itself not change the way farmers are managing their organic and mineral resources. This knowledge needs to be condensed in tools adapted to the clients targeted.

7. References

Akhtar, M. 2000. Effect of organic and urea amendments in soil on nematode communities and plant growth. Soil Biol. Biochem. 32:573-575.

Cadisch G., Giller K.E., Driven by nature: plant litter quality and decomposition, CAB International, Wallingford, UK, 1997.

Cadisch G., Handayanto E., Malama C., Seyni F. and Giller K.E., N recovery from legume prunings and priming effects are governed by the residue quality, Plant and Soil 205 (1998) 125-134.

Cong P.T., Improving phosphorus availability in selected soils from the uplands of South Vietnam by residue management. A case study: *Tithonia diversifolia*, PhD thesis, Katholieke Universiteit Leuven, Leuven, Belgium, 2000.

Dudal R., Forty years of soil fertility work in sub-Saharan Africa, in: B. Vanlauwe, J. Diels, N. Sanginga and R. Merckx (Eds.), Integrated Plant Nutrient Management in sub-Saharan Africa: from Concept to Practice, CABI, Wallingford, UK, 2001, In press.

IITA (International Institute of Tropical Agricultue), Sustainable food production in sub-Saharan Africa: 1. IITA's contributions, IITA, Ibadan, Nigeria, 1992.

Kimetu J.M., Mugendi D.N., Palm C.A., Mutuo P., Gachengo C.N., Kungu J. and Nandwa S., Nitrogen fertilizer equivalencies of organic materials of differing quality and optimum combination with inorganic nitrogen source, in: A. Bationo and M.J. Swift (Eds.), Proceedings of the 8th meeting of the African Network for Soil Biology and Fertility research, Nairobi, Kenya, 2002, In press.

Minhas P.S. and Gill A.S., Evaporation from soil as affected by incorporation and surface and sub-surface placement of oat straw, Journal of the Indian Society of Soil Science 33 (1985) 774-778.

Mucheru M., Mugendi D.N., Micheni A., Mugwe J., Kungu J., Otor S. and Gitari J., Improved food production by use of soil fertility amendment strategies in the central highlands of Kenya, in: A. Bationo and M.J. Swift (Eds.), Proceedings of the 8th meeting of the African Network for Soil Biology and Fertility research, Nairobi, Kenya, 2002, In press.

Murwira H.K., Mutuo P., Nhamo N., Marandu A.E., Rabeson R., Mwale M. and Palm C.A., Fertilizer equivalency values of organic materials of differing quality, in: B. Vanlauwe, J. Diels, N. Sanginga and R. Merckx (Eds.), Integrated Plant Nutrient Management in sub-Saharan Africa: from Concept to Practice, CABI, Wallingford, UK, 2001, In press.

Nhamo N., An evaluation of the efficacy of organic and inorganic fertilizer combinations in supplying nitrogen to crops, M Phil thesis, University of Zimbabwe, Zimbabwe, 2001.

Nzuma J.K. and Murwira H.K., Effect of management on changes in manure nitrogen during storage, in: M.J. Swift (Ed.), Report of the Tropical Soil Biology and Fertility Programme TSBF, 1997-1998, TSBF, Kenya, Nairobi, 2000, 26-29.

Oglesby K.A. and Fownes J.H., Effects of chemical composition on nitrogen mineralization from green manures of seven tropical leguminous tress, Plant and Soil 143 (1992) 127-132.

Okalebo J.R., Palm C.A., Lekasi J.K., Nandwa S.M., Othieno C.O., Waigwa M. and Ndungu K.W., Use of organic and inorganic resources to increase maize yields in some Kenyan infertile soils: a five-year experience, in: A. Bationo and M.J. Swift (Eds.), Proceedings of the 8th meeting of the African Network for Soil Biology and Fertility research, Nairobi, Kenya, 2002, In press.

Palm C.A. and Sanchez P.A., Nitrogen release from the leaves of some tropical legumes as affected by their lignin and polyphenolic contents, Soil Biology and Biochemistry 23 (1991) 83-88.

Palm C.A., Gachengo C.N., Delve R.J., Cadisch G., Giller K.E., Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database, Agriculture, Ecosystems and Environment 83 (2001) 27-42.

Sanchez P.A., Properties and Management of Soils in the Tropics, John Wiley and sons, New York, USA, 1976.

Sanchez P.A., Tropical soil fertility research: towards the second paradigm, State-of-the-Art lecture, Proceedings of the 15th International Soil Science Congress, Acapulco, Mexico, 1994.

Sanchez P.A. and Jama B.A., Soil Fertility replenishment takes off in East and Southern Africa, in: B. Vanlauwe, J. Diels, N. Sanginga and R. Merckx (Eds.), Integrated Plant Nutrient Management in sub-Saharan Africa: from Concept to Practice, CABI, Wallingford, UK, 2001, In press.

Sembiring H., Raun, W.R., Johnson G.V. and Boman R.K., Effect of wheat straw inversion on soil water conservation, Soil Scinece 159 (1995) 81-89.

Swift M.J., Soil biological processes and tropical soil fertility: a proposal for a collaborative programme of research, Biology International Special Issue 5, International Union of Biological Sciences, Paris, France, 1984.

Swift M.J., Tropical soil biology and fertility: planning for research, Biology International Special Issue 9, International Union of Biological Sciences, Paris, France, 1985.

Swift M.J., Tropical soil biology and fertility : inter-regional research planning workshop, Biology International Special Issue 13, International Union of Biological Sciences, Paris, France, 1986.

Swift M.J., Heal O.W. and Anderson J.M., Decomposition in Terrestrial Ecosystems, Studies in Ecology Volume 5, Blackwell Scientific Publications, Oxfort, UK, 1979.

Vanlauwe B., Diels J., Sanginga N., Carsky R.J., Deckers J., Merckx R., Utilization of rock phosphate by crops on a representative toposequence in the Northern Guinea savanna zone of Nigeria: Response by maize to previous herbaceous legume cropping and rock phospate treatments, Soil Biology and Biochemistry 32 (2000) 2079-2090.

Vanlauwe B., Wendt J. and Diels J., Combined application of organic matter and fertilizer, in: G. Tian, F. Ishida and J.D.H. Keatinge (Eds.), Sustaining Soil Fertility in West-Africa, ASA Special Publication, Wisoncsin, USA, 2001, In press.

Vanlauwe B., Aihou K., Aman S., Iwuafor E.N.O., Tossah B.K., Diels J., Sanginga N., Lyasse O., Merckx R. and Deckers J., Maize yield as affected by organic inputs and urea in the West-African moist savanna, Agronomy Journal (2002) In press.

Table 1: A brief summary of the science of tropical organic resource management.

Period	Scientific progress	Reference
< 1970s	Organic matter as a 'blob'	Palm, personal communication
1979	Organisms - Physical environment – Quality framework for organic matter decomposition	Swift et al., 1979
1984-1986	Development of the 'synchrony' research theme within the Tropical Soil Biology and Fertility programme	Swift, 1984; Swift, 1985; Swift, 1986
1990s	Various experiments addressing the 'synchrony' hypothesis	Various
1995	International Symposium on 'Plant Litter Quality and Decomposition'	Cadisch and Giller, 1997
2000	Development of the 'Organic Resource Database' and the Decision Support System for organic N management	Palm et al., 2001
> 2001	Quantification of the Decision Support System for organic N management	Future publications

Table 2: Treatment structures and year/season of implementation of the various experiments on organic-mineral interactions in West, East, and southern Africa. An appreciation of the rainfall received during the experiments is also given.

Site - country (reference)	Organic resources used (%N)	Mineral N used	Organic resources application rates	Mineral N application rates	Year – season[a]	Rainfall
Sekou - Benin (Vanlauwe et al., 2002)	*Leucaena leucocephala* (4.7%), *Azadirachta indica* (2.4%), *Senna siamea* (3.0%)	Urea	90 kg N ha^{-1} in sole; 45 kg N ha^{-1} in combined treatments	N response curve (0, 22.5, 45, 67.5, 90 kg N ha^{-1}); 45 kg N ha^{-1} in combined treatments	1997 – 1	Drought stress during flowering
Meru - Kenya (Mucheru et al., 2002)	*Leucaena leucocephala* (3.8%), *Calliandra calothyrsus* (3.3%), *Tithonia diversifolia* (3.0%), Cattle manure (1.4%)	Compound fertilizer (23:23:0)	60 kg N ha^{-1} in sole; 30 kg N ha^{-1} in combined treatments	60 kg N ha^{-1} in sole; 30 kg N ha^{-1} in combined treatments	2000 – 1	Low rainfall during first 20 days
					2000 – 2	Normal
Eldoret - Kenya (Okalebo et al., 2002)	Wheat straw (0.7%), Soybean trash (1.1%)	Urea	2 ton dry matter ha^{-1}	80 kg N ha^{-1} in sole; 20, 40, 80, and 100 kg N ha^{-1} in combined treatments	1997	Low rainfall and poor distribution
					1998	Normal
Various - Zimbabwe (Nhamo, 2001)	Cattle manure (2.6%)	Ammonium nitrate	25, 50, 75, and 100 kg N ha^{-1}	Complement organic resource application rates to reach 100 kg N ha^{-1}	1997/98	Normal
					1998/99	Normal

[a] Only given when more than 1 season per year occurs.

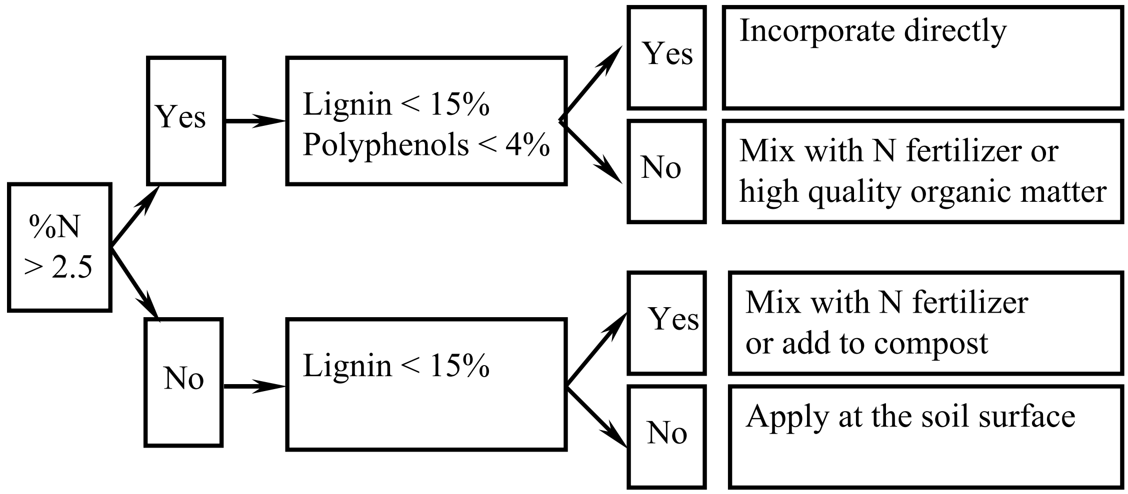


Fig. 1: The Decision Support System for organic N management, leading to 4 classes of organic resources (adapted from Palm et al., 2001).

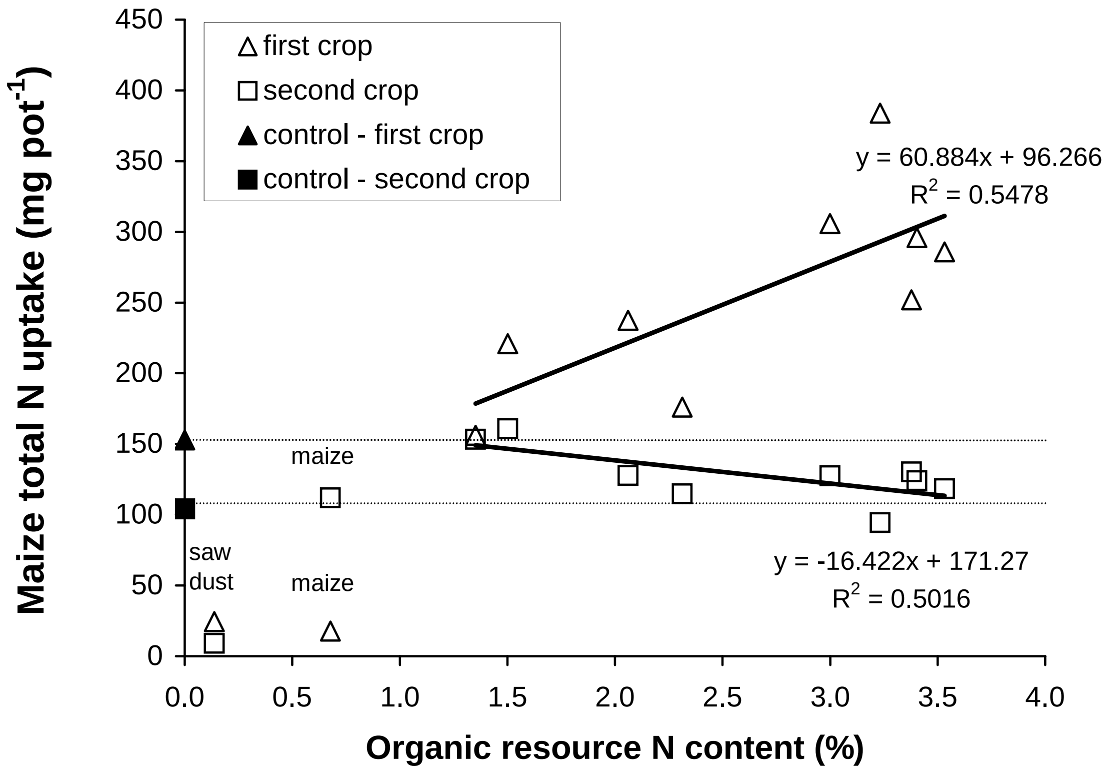


Fig. 2: Relationship between the N content of a wide range of organic resources and the total (shoot + root) N uptake by maize in a greenhouse pot trial. The regression equations were calculated for all residues excluding maize and sawdust. The dashed lines give the maize total N uptake in the control soils.

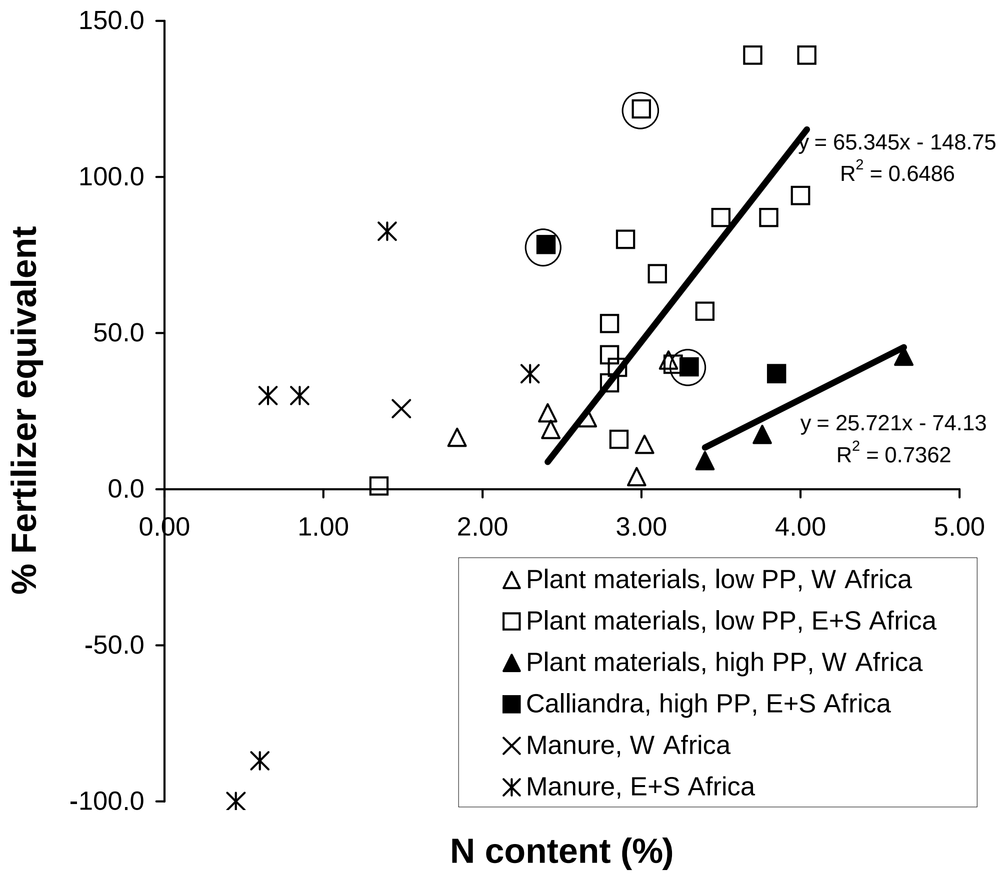


Fig. 3: Relationship between the N fertilizer equivalent and the N content of plant residues and manure for a series of sites in West (W), East and Southern (E+S) Africa. The linear regression equations were calculated separately for the plant materials with low and high polyphenol (PP) content. Encircled values were excluded from the regression analysis. Source: Vanlauwe et al. (2002), Murwira et al. (2001), Kimetu et al. (2002), Mucheru et al. (2002).

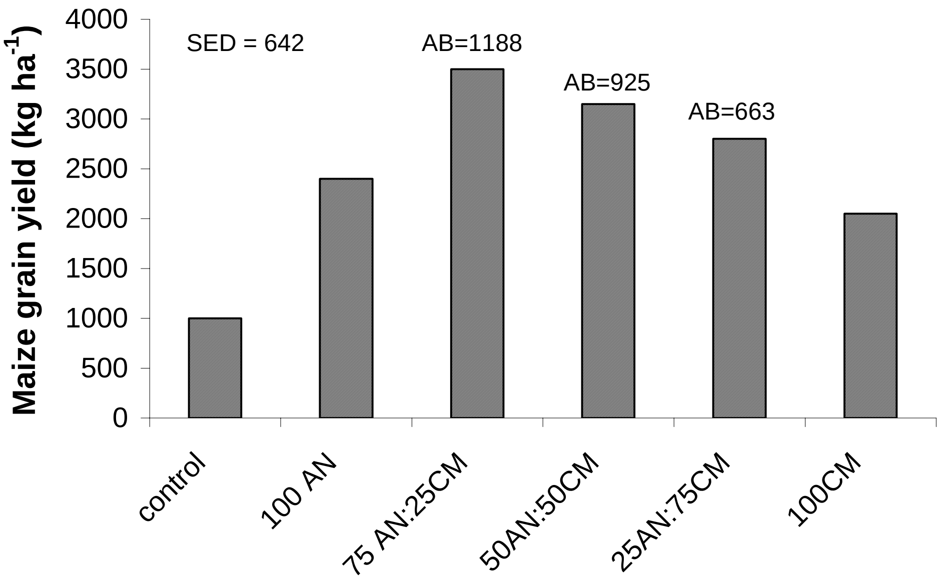


Fig. 4: Maize grain yield as affected by inputs of various combinations of cattle manure (CM) and ammonium nitrate (AN) for a series of on-farm trials (14 trials) in Zimbabwe. Data are averaged over all sites and two seasons. The added benefits (AB) (in kg maize grain ha^{-1}) have been calculated following equation 1. 'SED' means 'Standard Error of the Difference'. Adapted from Nhamo (2001).

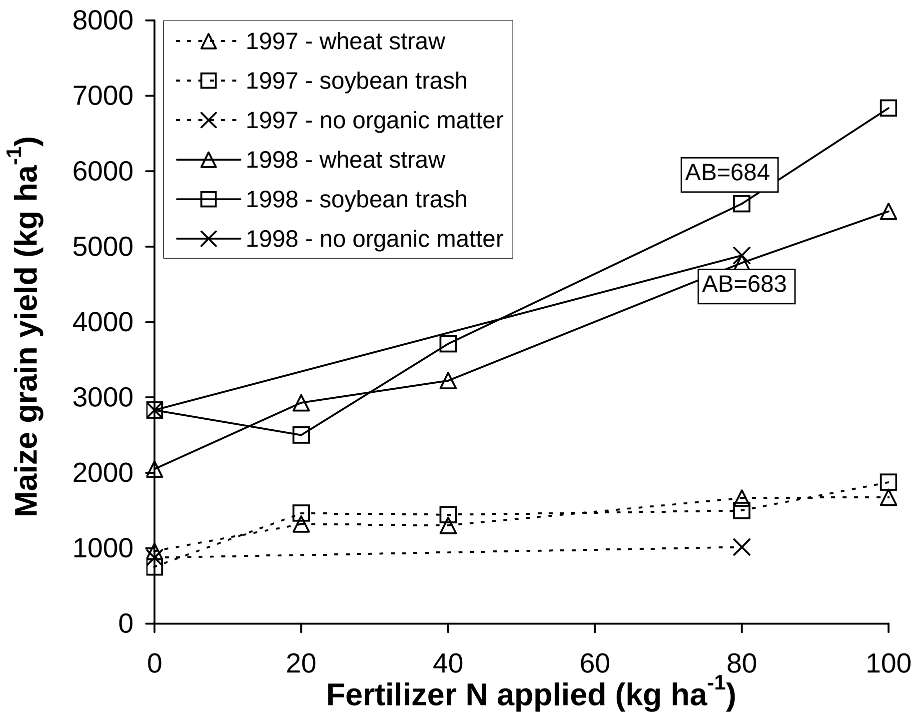


Fig. 5: Maize grain yield in 1997 and 1998 as affected by the application of low quality organic resources supplemented with various rates of urea for a site in central Kenya. The added benefits (AB) (in kg maize grain ha^{-1}) have been calculated following equation 1. Adapted from Okalebo et al. (2002).

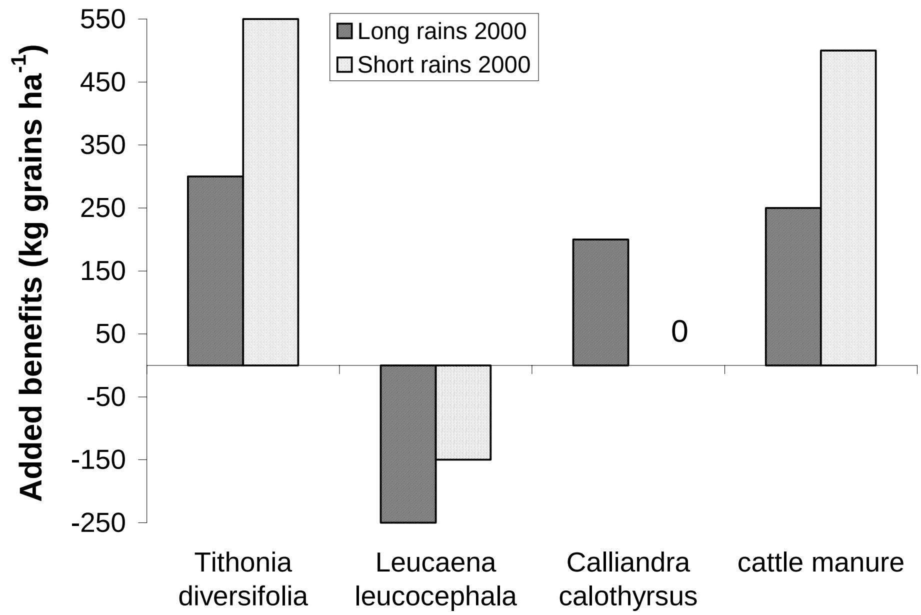


Fig. 6: Added benefits (in kg maize grain ha^{-1}) as affected by organic resource for 2 seasons on a site in central Kenya. The added benefits have been calculated following equation 1. Adapted from Mucheru et al. (2002).

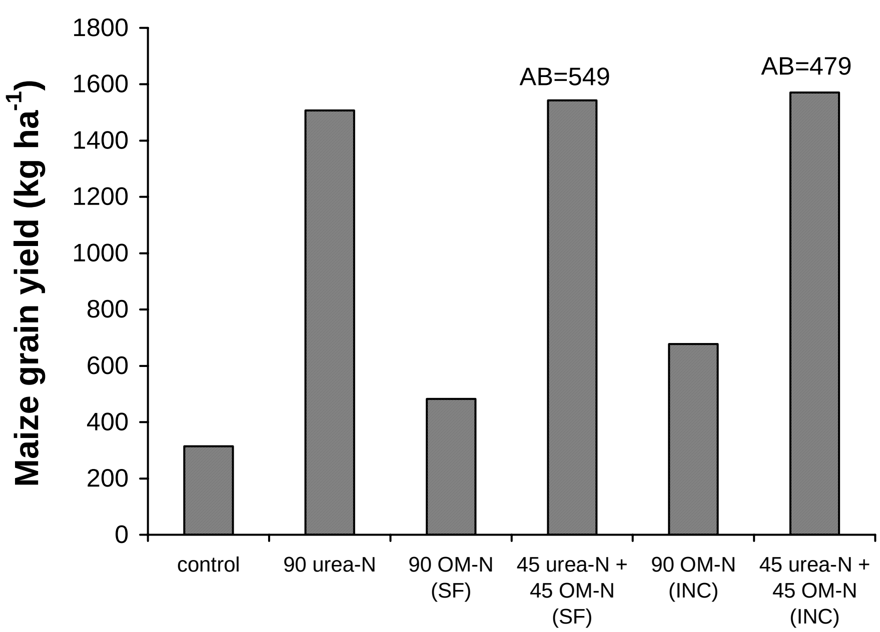


Fig. 7: Maize grain yields in Sekou as affected by the application of urea, organic materials, or the combination of both. 'SF', 'INC', and 'OM' mean 'surface-applied', 'incorporated', and 'organic matter', respectively. Numerical values for treatments are expressed as kg N ha^{-1}. The added benefits (AB) (in kg maize grain ha^{-1}) have been calculated following equation 1. Adapted from Vanlauwe et al. (2002).

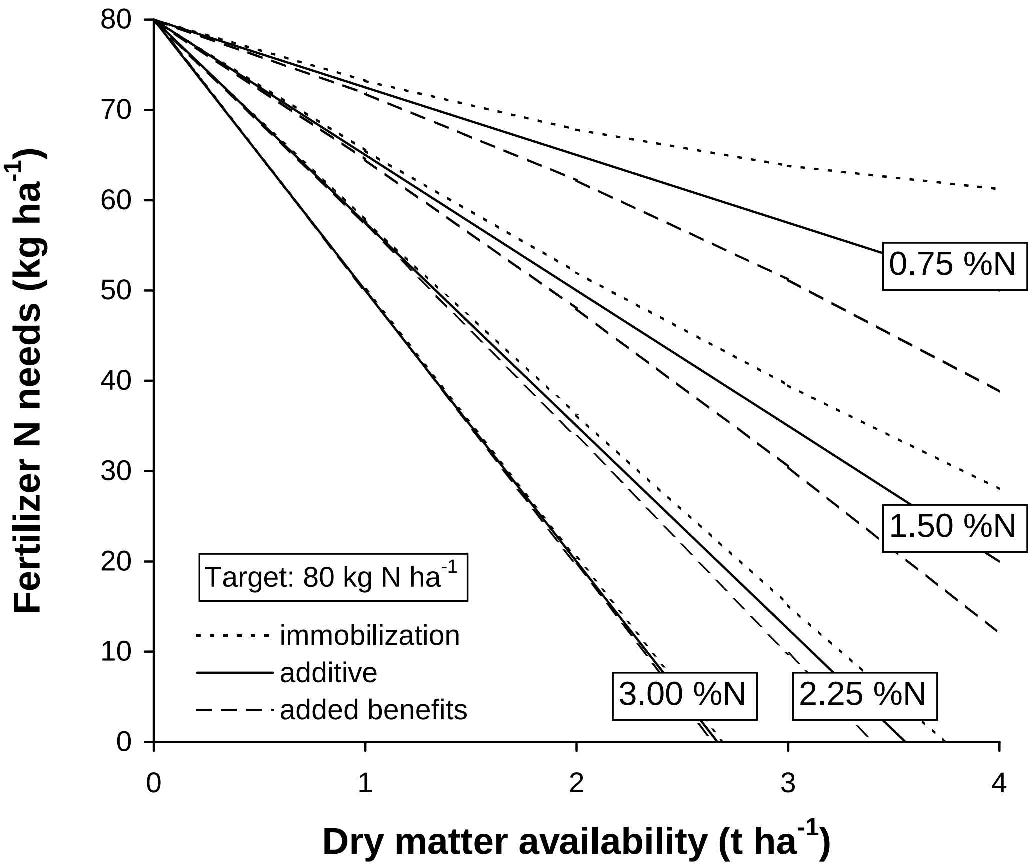


Fig. 8: Conceptual model for recommending the amount of N fertilizer needed for a specific targeted crop yield when a certain amount of organic matter with a certain quality is available. The model assumes that direct interactions between organic matter and fertilizer will be more substantial as the quality of the organic matter decreases. Depending on the duration of the immobilization, less (in case of temporary immobilization with reduced losses of fertilizer N) or more (in case of prolonged immobilization, e.g., with sawdust – Fig. 2) N fertilizer may be required to reach the same target (here hypothetically set at 80 kg N ha^{-1}).

Submitted to Agriculture and Human Values

Using decision guides on manure use to bridge the gap between researchers and farmers.

Herbert K. Murwira*, Killian Mutiro and Pauline P. Chivenge
Tropical Soil Biology and Fertility Program (TSBF Zimbabwe), c/o Faculty of Agriculture, University of Zimbabwe, P.O.Box MP228, Mt Pleasant, Harare, Zimbabwe
*Corresponding author's E-mail: hmurwira@zambezi.net

Abstract
A lot of work has been done to assess the value of manure as a plant nutrient source, characterize its quality, and on ways of improving its effectiveness through better storage or integrated use with inorganic fertilizers. While the knowledge gained on manure use has been immense; the information has hardly been translated into a useable form for farmers and extension. There are no effective messages that research and extension has passed on to farmers. There is a growing need to develop communication strategies that could effectively link farm practice with research results and ultimately bring about a positive change in the way farmers manage resources available to them. This paper presents some decision guides developed for manure use based on both researchers' understanding and farmer perceptions. The decision guides have been field tested and developed further following discussions held with farmers. The usefulness of the decision guides as communication tools to enhance uptake of soil fertility management options is discussed.

Key words: manure, decision guides, farmer perceptions

Introduction
Much work has been done on understanding the effects of manure on crop response, and on manure quality and how quality can be improved by better methods of composting and beneficiation with inorganic fertilizers especially rock P (Mugwira and Murwira, 1997). Several workers have reported the beneficial effects of combining manure with inorganic fertilizers (Murwira, 1993; Mubonderi, 1999; Nhamo et. al., 2001, Munguri ,1996). Use of combinations can help synchronise nutrient supply and crop uptake, improve on-farm nutrient cycling, reduce environmental pollution (N and P) and be used to manage mineralisation-immobilisation processes. Placement studies have also shown that broadcasting manure was less effective than banding and station placement (Munguri, 1996).

Recommendations on rates of manure application for field crops are varied but difficult to compare across sites because nutrient content data is often not cited (Mugwira and Murwira, 1997). It is however difficult to come up with prescriptive guidelines on use of manure as the quality varies considerably from farmer to farmer because of they way it is managed and stored prior to application in the fields (Murwira et al, 2001). Our challenge is to translate the scientific understanding we have into farm practice taking into consideration quality and quantity of manure available, short- and long-term effects, economic factors, environmental factors, farmer perceptions and limiting nutrients. This requires sharing with farmers the scientific principles of using manure and the development of communication strategies that could bring about a positive change in the way farmers manage resources available to them. Understanding farmer decision making is a key to this process and we advocated in this study an approach that entails the development and use of decision guides to bridge the gap between researchers and farmers.

It has been argued that farmers make decisions on fertilizer and organic resource use in a decomposed fashion using relative comparisons of singular alternatives rather than holistic assessments of utility (Schoemaker, 1982). In other words the decision to use a specific type of input, its utility, is based on asking oneself a series of questions that lead a choice. The decision making process can thus be described as a decision tree which is a sequence of discreet decision criteria, all of which have to be passed along a path to a particular outcome or choice (Gladwin, 1989). The biggest assumption behind the use of decision guides is that the decision-makers themselves are the experts on how they make the decisions they take. Therefore it is crucial to elicit from the decision-makers themselves their decision criteria which can then be presented in the form of a decision tree.

Early decision trees attempted to use socio-economic variables such as labour availability, cash income, livestock ownership etc to arrive at 'recommended actions' for different socio-economic scenarios. Using a reductionist logic based on binary oppositions (e.g. livestock owners Vs non-livestock owners, female headed Vs male headed households, labour-rich Vs labor-poor farmers etc), it was assumed that an analyst could determine the series of decisions which farmers should make when choosing between technological options. The main criticism is that such decision trees can never sufficiently mimic the much more diverse and dynamic realities under which different individual farmers operate. For example, it is not always possible to conclude that a livestock owner should behave differently from a non-livestock owner because the latter may use a number of local arrangements and networks to gain access to cattle or cattle resources. Similarly a 'resource poor' farmer may suddenly find himself or herself with sufficient inorganic fertilisers accruing from different possible sources. In such situations, individuals do not stop and say, 'since I am classified as a resource-poor farmer in a decision tree, I will manage my fertiliser in this way'. The bottom-line is that the binary permutations constructed by analysts in the form of decision trees cannot capture the flow and flux of everyday life, which determine farmer decision making and choices. Also it is necessary to make a distinction between describing what farmers do and offering them options e.g. what can you do if you have livestock or if you have livestock you can do the following.

Other types of decision trees have binary categories that are constructed on the basis of relatively stable bio-physical variables such as N content, lignin content etc (Palm et. al, 1997). These variables are not amenable to direct manipulation by individual farmers, nor are they subject to sudden socio-economic upheavals such as credit availability, access to markets and so on. Having said so, it is important to recognize that farmers' decisions are based on a judgement between options that relate to the whole range of economic, cultural and biological parameters (Swift et. al, 1994). Categories are also less fixed than may be apparent (Palm et. al., 2001) because of modifiers which for example, polyphenols, may affect nutrient release.

Given the apparent weakness in the two approaches discussed above, there exists a strong argument for the integration of socio-economic variables in natural resource management decision trees. In this case, the challenges are there but not insurmountable. The first challenge is that these decision trees should not be seen as recipes for action but as sets of options which farmers can validate and 'ground truth' to suit their own individual circumstances. This requires a joint learning process between researchers and farmers. The immediate challenge is to determine the most suitable ways in which this joint learning can take place in terms of what tools and platforms to use. There is an urgent need to test a range of practical tools to communicate scientific principles to farmers through use of 'farmer friendly decision trees'. This study is an attempt to derive decision guides for manure use. The objective of formulating the decision guides were two fold:

1. to document how farmers use the available manure and,
2. to use the decision guide as a tool to identify opportunities in manure management and enhancement of soil fertility.

Materials and methods

The study was an attempt to come up with a framework for developing manure decision guides based on both research and farmer perceptions and understanding. The starting point for the study pivoted around the key question of what type of guide should be developed and the target clientele. Would there be separate guides for research and extension and one for farmers? For which nutrients and for what crops? An even more important question was how do we integrate what farmers are doing into research recommendations? Are research recommendations and farmer perception compatible? In this regard it was important to establish farmers' characterization of quality- especially the range of manure qualities found.

A draft guide was synthesized from available research information by the authors to design a single framework representing the essential elements required in providing researchers and extension with a tool for manure management. The framework was further distilled through peer review after which it was field-tested with a group of 50 farmers in Mfiri village, Shurugwi District, Zimbabwe. Testing of the decision guide was carried out to identify gaps and weaknesses in its thought flow (presentation) and content. The decision guide was presented to farmers and the field testing of the guide took three forms:

1. eliciting information to improve the guide in group discussions,
2. eliciting information on decision criteria used by farmers when using manure (focus group discussions to develop a farmer guide), and,
3. Personal interviews to get information on specific household management practices.

In order to incorporate farmer perceptions into the design of the guide, focus discussions to find out current manure use practices were held with discussions centered on manure quantities available, quality, curing methods, methods of application and supplementation. Household interviews were conducted with four farm families that were randomly picked from the large group of almost 50 farmers. The sample size was small, but nevertheless targeted at bringing out the diversity in individual practice and the elements that farmers consider being important for inclusion in a decision guide. These personal interviews provided an opportunity to explore further the issues that came up from the large group discussions.

After the meetings with farmers, the results of the field testing of the guide were evaluated and changes incorporated into the research and extension guide. A second framework was developed based on the discussions held with farmers. A spidogram or web analysis was used as a tool for eliciting and summarizing information on the management framework used by farmers. The web analysis allowed participants to draw out the complex, inter-linked relationships among effects, causes or factors during decision making.

Results

The challenge in developing research and extension guides is making sure that they are technically precise. Scientific insights into mineral release and fertilizer equivalence require that for such a guide to be useful, it must differentiate the use of different quality manures and the conditions that lead to those differences in quality. It came out clearly in the study that other useful categorizations in the research guide could be based on socio-economic variables such as livestock ownership (numbers owned and access to manure) as well as biophysical factors like use and type of residues in kraals, type of feed, quantity, storage and chemical characteristics which influences manure quality. An interesting result of the survey was farmers have their own indicators of quality and these include presence of moulds, colour, compactness, lumpiness, and texture. These indicators are qualitative but are useful to incorporate in a technical guide.

Rates of application of manure are very variable even for the same farmer. There are seasonal variations of rate based on previous crop performance, quantities of manure available and manure rotations/cycles within a field. The frequency of manure application ranged from two to four years depending on the number of livestock hence quantity of manure a farmer had, and the residual effects of previously applied manure (Table 1). An interesting point that came from the discussions with farmers was that all available manure was used irrespective of quality but that use practice could be dependent on quality. From the personal interviews it was clear from some farmers that poor quality manure was most often broadcast whereas high quality manure was banded. Fields considered as breadbaskets are targeted for manure application. Some farmers use high rates of application if quality was poor and where fertilizer is available they supplement with large rates of nitrogenous fertilizer. Rate of fertilizer supplementation depends on crop performance and available income to purchase inorganic fertilizer.

Using the above information from farmers and from secondary data combined with scientific understanding of nutrient management, a research and extension guide was developed (Fig.1). The guide has two major components; the first (in the upper box) focussing on manure production and storage and their impact on quality, and the second emphasizing management of different quality manure. The guide is not crop specific but there is implicit recognition that farmers in Zimbabwe where the guide is initially targeted give priority to maize and vegetables. The management systems that the guide attempts to address are complex and depend on individual decision making and the soil type at any particular location and other household labor limitations.

Decision-making and manure use: the farmer's view

The results presented in this section were from discussions with a focus group involved in analyzing decision criteria. Decision-making by the farmers was analyzed through a spidogram approach culminating in the development of a farmer derived decision framework (Fig.2). One farmer presented the guide to the larger group of farmers after which it was further refined. The salient features of the farmer decision guide were that:

1. Farmers have a range of options that they use for soil fertility improvement as shown in the upper sections (A) of the diagram in Fig 2.
2. Farmers value quantity as being more important than quality of manure. This could be an indication that farmers are primarily more interested in the amount of resources they have and the extent to which they can be spread around over the farm. This seems rational as the larger the quantity, albeit of poor quality manure, the more nutrients they will be adding to the soil. There are also other secondary benefits of organic matter addition such as increase in water holding capacity, increased nutrient use efficiencies etc. As a result, farmers have developed several strategies to improve the quantity of manure obtained from their kraals (Fig.2, B). These include adding anthill soil, crop residues, leaf litter etc. From the discussions there appeared to be a strong realization by farmers that management affects quality. Farmers however do not deliberately manage or manipulate quality of manure to target it to a specific crop even though they might have preferences of which crop to apply higher quality manure (Fig 2, C and D). Residues are added primarily to increase quantity though they may have a secondary effect on manure quality. There is a limit to which residues can be added to the kraal, however.
3. Farmers are vague on rates, which maybe a reflection of a lack of consensus within a large group but also of wide differences between households. However they have guides on how to target manure application.
4. The quantity of manure that is pit stored is likely to remain small as some farmers feel that they have limited labor available.

Discussion

The farmer framework is much more comprehensive than the research and extension guide and probably fits more within their environment. Concerns were raised that the farmer guide is more likely to vary from area to area. A useful decision guide should be generic allowing for modifications to be made as circumstance change. The farmer guide was useful as a training tool to let farmers be more aware of the need to manage quality as well rather than quantity of manure alone. There was broad consensus that the research extension guide should be technically precise.

There is a big gap that needs to be filled on farmer quality characterization. It will be necessary to more thoroughly ascertain the range of manure qualities that are identifiable by farmers, and how the identifiable indicators differ with region, and whether those indicators are socially differentiated. A pertinent question for research is whether there is a clear color pattern associated with stage of decomposition? If so then this opens up the potential to use color charts as indicators of quality and hence of how a particular manure could be managed. There is need to look at farmer indicators and how they relate to laboratory indices. Farmer quality indices might need to be considered in combination and not individually.

The farmer-developed manure guide still looks complex despite the fact that it was presented by a farmer to a larger audience of farmers. Opportunities for the further simplifying it should be identified. There is no doubt that farmers were excited by the manure decision guide hence it would be worthwhile to expand the range of decision guides that could be developed for the many options that farmers have for soil fertility improvement (Fig.2). Whilst a singular decision tree for a particular option forms the best way of exploring the way it is managed and how its management can be improved, farmers are most often managing combinations of different resources. The challenge therefore remains of how to integrate use of different decision trees for optimal management of multiple resources. For example, how do legumes fit within intervening years of the manure cycle etc. Similarly, a range of platforms and learning spaces suitable for different categories of farmers should also be identified and tested (these could range from nutrient test strips to village labs and pot experiments).

Conclusions

A lot of issues have been raised above. Critical among those issues is to continue testing the decision guides and ensure that they are robust and applicable (but not necessarily) to a wide range of environments without losing the context of farmer circumstances. The question of validation should be left to farmers while the main role of the scientist should be that of facilitating this process of validation. Validating decision trees should not be viewed more in terms of going out in the field to prove a scientific point, but rather in terms of enabling farmers to test our scientific models.

In order for farmers to validate decision trees, they must understand the basic scientific principles from which scientists derived them, and this can only be done through a process of researcher farmer dialogue and mutual learning. By the same token the joint learning process should also enable scientists to refine and adjust their scientific models by closely observing how and why different farmers are making their choices.

Acknowledgements

The support of the IFAD and the Rockefeller Foundation is greatly appreciated. The contributions of M. T. Kamanda, G. Mawere, T. Mubonderi, M. Mudhara, L.M. Mugwira, J. Mutihero, K. Mutiro, N. Nhamo, J. Nyamangara, and D.B. Shumba are greatly acknowledged. Mrs D. Shumba worked tirelessly to make the field visits a success. This report was inspired by ideas of the late Dr Patrick Sikana.

References

Gladwin C.H.1989. Indigenous knowledge systems, the cognitive revolution, and agricultural decision making. Agriculture and Human Values, 32-41.

Mubonderi T. 1999. Cattle manure and inorganic fertilizer management for dryland maize production in the smallholder sector of Zimbabwe. Mphil thesis (Unpublished)

Mugwira L M and Murwira H K. 1997. Use of cattle manure to improve soil fertility in Zimbabwe: Past and current research and future research needs. SoilFertNet research results working paper No.2. 18pp.

Munguri M W, Mariga I K, and Chivinge O A. 1996. The potential of optimizing cattle manure use for maize production in Chinyika Resettlement Area, Zimbabwe. In: Research results and Network Outputs in 1994 and 1995. Proceedings of SoilFertNet meeting, pp 46-53.

Murwira H K. 1993. N dynamics in a sandy soil under manure fertilization. Unpublished PhD thesis.

Murwira,H K,.Mutuo P, Nhamo N, Marandu A E, Rabeson R,.Mwale M and.Palm C A. 2002. Fertilizer equivalency values of organic materials of differing quality. In: B.Vanlauwe, J.Diels, N.Sanginga and R.Merkx (eds), Integrated nutrient management in sub-Saharan Africa. CABI p113-122.

Nhamo N, Murwira H K and Giller K. 2001. The effects of combining cattle manure and inorganic fertilizer on maize yields in Zimbabwe. Submitted to Field Crops Research.

Palm C A, Myers R J K and Nandwa S M. 1997. Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. In: Buresh R J, Sanchez P A and Calhoun F (eds), Replenishing soil fertility in Africa. SSSA Special publication No.51 pp193-218. .

Schoemaker P. 1982. The expected utility model: its variants, purposes, evidence and limitations. Journal of Economic Literature 20:529-563.

Swift M J, Bohren L, Carter S E, Izac A M and Woomer P L. 1994. Biological management of tropical soils: Integrating process research with farm practice. In: The biolgical management of tropical soil fertility. Ed. P.L.Woomer and M.J.Swift. John Wiley & Sons pp209-228.

Table 1. Diversity in manure management and fertilizer use strategies for different farmers in Shurugwi District, Zimbabwe.

	Manure Management and Use			**Mineral Fertilizer Use**	
	Rate of Application	Method of application	Manure Application Rotations	Type of Fertilizer	Rate of application
Farmer 1	4t/ha 17t/ha	Broadcasted Banded	2 year rotation maize-g/nut-maize	AN applied	Uses Coca – Cola bottle top for pit stored manure And cup number 2.5 for heap stored manure
Farmer 2	21t/ha- first season 16t/ha – second season	Broadcasted	3 year rotation maize-maize-g/nut	No mineral fertilizer for pit stored manure Used to apply AN when using heap stored manure	Could not give rate of application of AN when heap stored manure was used
Farmer 3	3t/ha banded and an additional 4t/ha broadcasted	Banding and broadcasting	3 year rotation maize-maize-g/nuts	No ammonium nitrate applied	Seems application of AN is targeted or done only when crop deserves it
Farmer 4	Banded at 2 cm depth in ridge	Banding	2 year rotation maize-g/nuts-maize	No ammonium nitrate applied	Seems application of AN is targeted or done only when crop deserves it

Note: Application rates were converted from scotch carts to tonnes per hectare and each scotch cart can carry approximately 400kg of manure.

Fig.1.Researcher developed manure decision guide

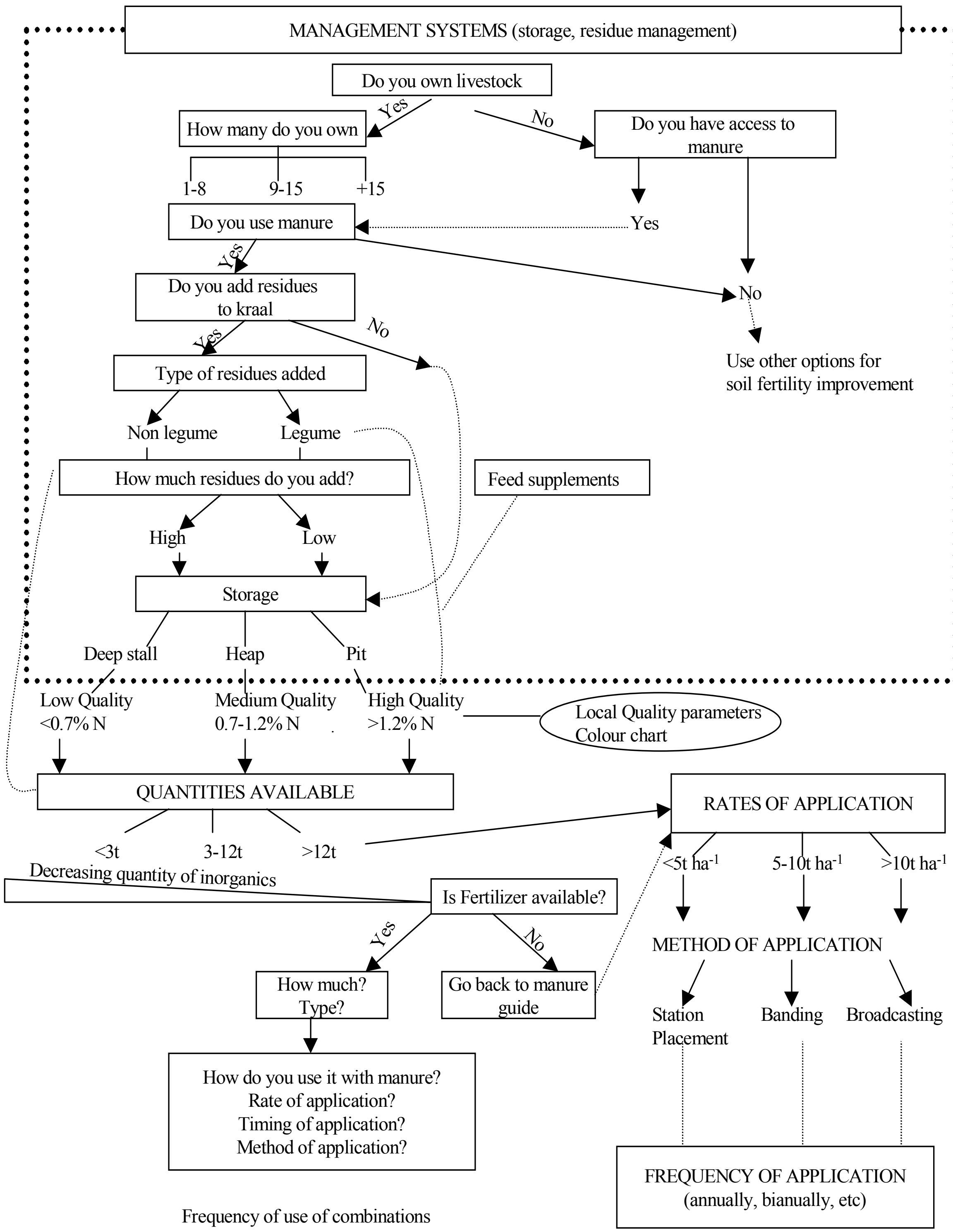
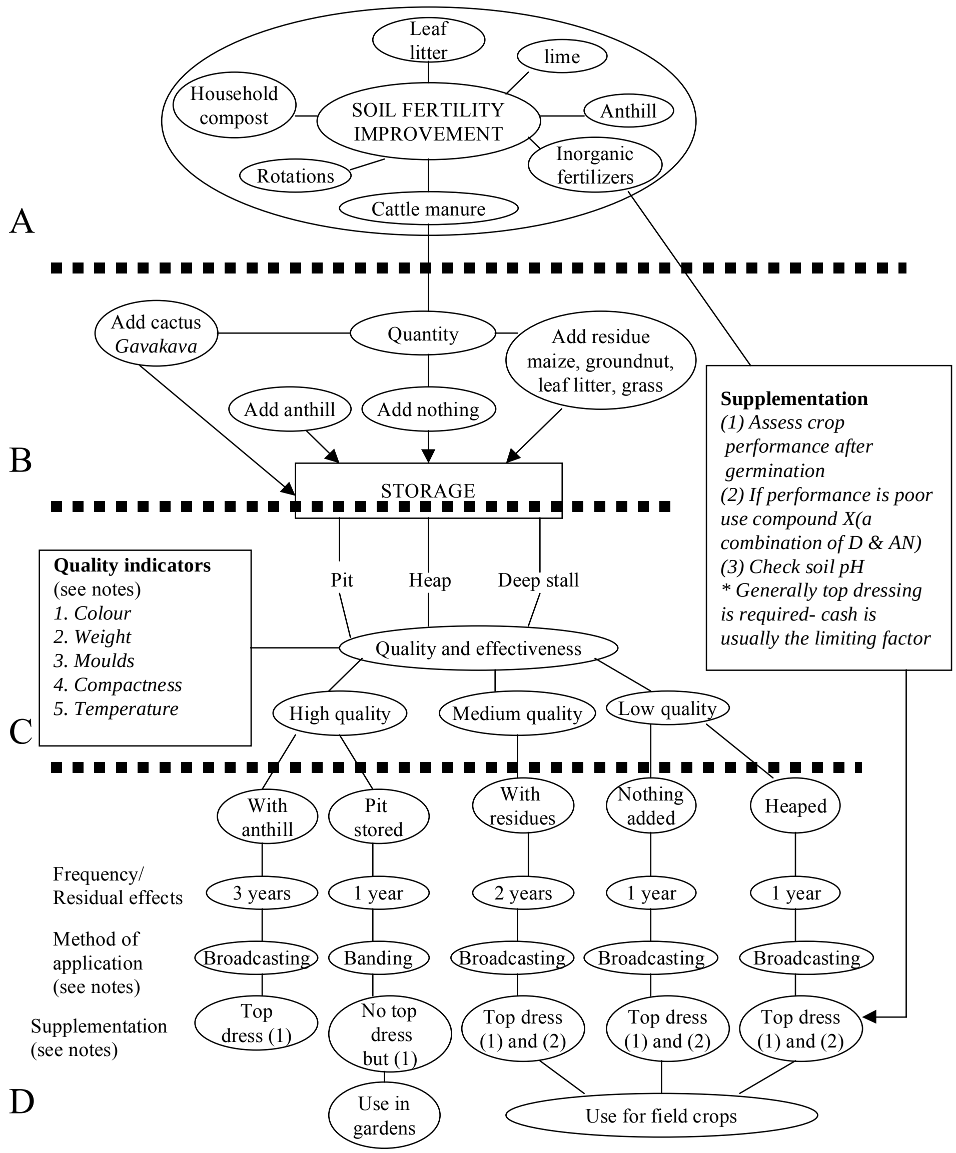


Fig.2. Farmer manure decision guide developed using a spidogram analysis



Notes on rates of manure application

- It depends on the quantities of manure available
- Rotations of manure application depend on the plot/farm size
- Manure is usually targeted for high potential fields (for food security)

Considerations

- Soil type
- Presence of witch weed-striga

Low rates or no manure applied to low potential fields

Draft

Efficacy of soil organic matter fractionation methods for soils of different texture under similar management.

Pauline P. Chivenge[1*], Herbert K. Murwira[1] and Ken E. Giller[2]
[1]Tropical Soil Biology and Fertility (TSBF), P O Box MP 228, Mt Pleasant, Harare, Zimbabwe.
[2]Soil Science and Agricultural Engineering Department, Faculty of Agriculture, University of Zimbabwe, PO Box MP 167, Mt Pleasant, Harare

Abstract
High soil dispersion is essential for the effectiveness of physical soil organic matter fractionation methods based on fraction size and/or density. A study was conducted to test the use of two dispersing agents, sodium resin bags and sodium hexametaphosphate for organic matter fractionation in two soils, a sand and a red clay soil. Two concentrations of sodium hexametaphosphate, 0.5% and 2% were used, and for the 2% concentration another treatment of pre-soaking versus not soaking was added.

Complete dispersion was achieved with all the dispersing agents used for the sandy soil. For the red clay soil none of the dispersing agents used achieved complete dispersion. Compared with the sodium hexametaphosphate, sodium resin bags resulted in a three-fold decrease in the amounts of coarse organic matter fractions for both the sand and the red clay soils. The use of resin bags resulted in a decrease in the amount of organic C in the coarse sand (212-2000 μm) and the medium sand (53-212 μm) fractions. There were however no differences in the amounts of the mineral fractions obtained by using the two dispersing agents for the two soil types.

Increasing the concentration of sodium hexametaphosphate did not result in an increase in soil dispersion for both the sand and red clay soils. There were no differences in the amounts of organic and mineral fractions obtained using the two concentrations for both the sand and red clay soils. Pre-soaking the soil resulted in an increase in soil dispersion reflected by a decrease in the amount of coarse sand and medium sand mineral fractions for the red clay soil. There were no effects on soil dispersion caused by soaking on the sandy soil. There were however no differences in the amounts of coarse and medium sand organic matter fractions obtained before and after soaking the soil. We concluded that using 0.5% sodium hexametaphosphate after soaking the soil was the most appropriate dispersing agent to use for achieving high soil dispersion without altering the soil organic matter distribution in the various size fractions for the red clay and the sandy soils.

Key words: *soil organic matter, soil organic matter fractions, soil dispersion, and dispersing agent*

Introduction
Soil organic matter (SOM) plays an important role in determining the fertility and productivity of soils and hence the need to understand more clearly the factors that control SOM dynamics as affected by land use management practices. The association of organic matter with particular constituents of the mineral soil may be important in regulating the mineralization and storage of SOM. Pools of organic matter with different stabilities provide a spectrum of nutrient availability that have different rates of release and are susceptible to different kinds of disturbance (Woomer et al., 1994). The ability to quantitatively estimate SOM fractions is important for understanding SOM dynamics in agricultural systems.

Several chemical and physical methods have been developed to separate SOM fractions. Chemical separation methods yield fractions that are not closely related to functions of SOM (Blair *et al.*, 1997) to soil processes such as aggregation and organic matter mineralization (Stevenson and Elliot, 1989; Feller and Beare, 1997). These methods give information on the kind of organic matter present that may vary in age and N content (Duxbury *et al.*, 1989). Chemical fractions (humic and fulvic acids) generally have a low turnover rate and are therefore not necessarily implicated in the short-term processes commonly studied in cultivated soils (Feller and Beare, 1997). Physical fractionation yields functional

SOM pools which differ in composition and biological function as they give information on where the organic matter is located (Elliot and Cambardella, 1991).

The effectiveness of soil dispersion with minimum alteration of associated organic matter, is crucial for physical fractionation. Limited dispersion of soil may result in the recovery of the most easily dispersed part of the fraction, or the recovered fraction may consist of an unknown mixture of primary particles and microaggregates of the same size but belonging to different size classes (Sanchez *et al*. 1989). Soil disruption is more rapid and complete with sandy soils than with heavy textured soils (Stevenson and Elliot, 1989). Soil dispersion can be achieved by sonication or shaking. Sonication can achieve high dispersion but it results in the breakdown of organic matter into finer particles (Feller and Beare, 1997) and produces heat, which might alter organic matter composition (Stevenson and Elliot, 1989). Shaking reduces organic matter redistribution. It can be done in water with or without glass beads, or after chemical pre-treatment of soil with sodium saturated chemicals.

The work reported in this paper is part of a broader study to determine the effects of tillage on SOM dynamics in a long-term experiment. The experiment was carried out at two sites in Zimbabwe, on a sandy soil (Udic Kandiustalf- USDA) at Domboshawa and on a red clayey soil (Rhodic Paleustalf- USDA) at the Institute of Agricultural Engineering (IAE) in Hatcliffe Harare. Before following the dynamics of SOM in these soils initial studies were conducted to test and establish methods for the fractionation of SOM. The methods tested are based on similar principles (physical- particle size separations) but use different dispersing agents. The degree of dispersion of aggregates was used as the criterion for choosing one method.

The objectives of this experiment were to assess the effectiveness of soil dispersion for two soil types (a sand and a red clay soil) under different tillage treatments by a) using sodium resin bags and sodium hexametaphosphate, b) two concentrations of sodium hexametaphosphate (HMP) 0.5 % and 2%, and c) pre-soaking the soil before shaking. It was hypothesized that a) higher dispersion would be achieved with the use of sodium resin bags than with sodium hexametaphosphate, b) increasing the concentration of sodium hexametaphoshate would increase the degree of dispersion, and c) pre-soaking the soil before shaking would increase soil dispersion.

Materials and Methods

The tillage experiments that were established in 1988/89 season at Domboshawa and Institute of Agricultural Engineering (IAE), Harare were used for this study. There were five tillage treatments, mulch ripping, conventional tillage, tied ridging and clean ripping. Soil samples were collected in October 1998 and passed through a 2 mm sieve.

Soil dispersion was done in sodium hexametaphosphate at two concentrations, 0.5% and 2%, and sodium resin bags, which were regenerated in 3M trisodium citrate. For soil dispersed in 2% sodium hexametaphosphate one set of samples was soaked in water overnight before shaking while for the other set there was no soaking. Fractionation was carried out by sieving the soil through two sieves to get the following size fractions, size fractions 212-2000 μm, 53-212 μm and 0-53 μm. The 53-212 μm size fraction of soil shaken in sodium resin bags was shaken for 1hr in resin beads to allow for further disruption of aggregates. The fractions were viewed under a binocular microscope to check for purity of the fractions and degree of dispersion of aggregates.

The 212-2000 μm and 53-212 μm organic matter fractions were analysed for organic carbon using a Leco Carbon Analyser. Organic C in the 0-53 μm fraction was not analysed for organic C.

T-tests for paired observations using Genstat 5 Release 4.1 were done to test for differences in using the different dispersing agents.

Results

The effects of texture on soil dispersion

For the red clayey soil none of the dispersing treatments achieved complete dispersion. This was observed under a binocular microscope, by the presence of micro-aggregates in the mineral fractions and mineral particles coating the organic matter fractions. For the sandy soil, however, complete dispersion of aggregates was achieved with all the dispersing agents used. The mineral fractions did not show the presence of micro-aggregates while the organic matter fractions were not coated with mineral fractions.

The effectiveness of dispersing agents

Sodium resin bags and sodium hexametaphosphate were effective in achieving complete soil dispersion in the sandy soil. There were no significant differences in the amount of fractions separated using the different dispersing agents except for the coarse organic matter fractions separated using the resin bags. There was a reduction in the amount of coarse sand organic matter fraction separated using resin bags compared with sodium hexametaphosphate (Table 1).

For the clayey soil none of the dispersing treatments used achieved complete dispersion. The use of resin bags increased dispersion of aggregates but reduced the amount of coarse organic matter recovered compared to sodium hexametaphosphate (Table 1). There was a slight but not significant decrease in the coarse mineral fraction and an increase in the intermediate mineral and mixed fractions obtained with the resin bags compared with sodium hexametaphosphate. There were significant differences in amounts of fractions dispersed in 2% hexametaphosphate and resin bags. Sodium hexametaphosphate gave higher amounts of the coarser fractions than resin bags (Table 1).

Increasing the concentration of sodium hexametaphosphate from 0.5 to 2% did not result in an increase in soil dispersion for the red clayey soil. There were no significant differences in the mass of the organic matter and mineral fractions obtained using the two concentrations.

Effects of dispersing agents on organic C distribution

The reduced amount of organic matter after using resin bags might have been a result of purer fractions being obtained. To see if the reduction in the amount of organic matter was a result of an increase in purity of the organic matter fractions, the fractions were analysed for organic C. The use of resin bags resulted in the reduced amount of organic C in the coarse organic matter fractions than sodium hexametaphospahte (Table 2).

Effects of soaking

For the red clay soil pre-soaking gave lower amounts of the mineral fraction with fewer aggregates than without soaking for separations done in 2% sodium hexametaphosphate (Table 3). Soaking did not however result in differences in the coarse organic matter fractions. Soaking did not result in differences in the masses of fractions obtained for the sandy soil.

Effects of tillage treatments on the effectiveness of dispersion

The effectiveness of aggregate dispersion was not affected by the different tillage treatments. The response of the different tillage treatments was the same across all the dispersing agents used.

For the red clay soil conventional tillage and clean ripping had similar amounts of coarse and medium sand organic matter fractions although clean ripping had higher amounts of total organic C than conventional tillage (Table 4). In the fine sand fraction clean ripping had higher amounts of organic matter than conventional tillage. Mulch ripping had higher total organic C, coarse and medium sand fraction organic matter contents than clean ripping (Table 4). Tied ridging had the highest total organic C (20.4 mg C g^{-1} soil) and sand fractions organic matter contents in the red clay soil (Table 4).

Bare fallow showed the highest decline in soil organic matter content as indicated by the lowest total organic C content (2.2 mg C g^{-1} soil) and smaller amounts of organic matter in all the organic matter fractions separated (Table 5). Conventional tillage had low total organic C content and low amounts of organic matter sand size fractions. Mulch ripping had higher total organic C amounts of sand size fractions than clean ripping (Table 5). Tied ridging had similar total organic C and amounts of organic matter in the sand fractions with clean ripping (Table 5). Hand hoeing had lower total organic C content and organic matter in the sand fractions than mulch ripping except for the fine sand fraction where there were no treatment differences (Table 5).

Discussion

Effects of texture on soil dispersion

There was no complete dispersion for the red clayey soil probably due to the high clay content (>40%) which results in the formation of strong bonds between mineral and organic particles to form micro- and macro-aggregates. Clay particles have high surface area and tend to form strong mineral-mineral and ogano-mineral interactions that require high force to disrupt. In the sandy soil there was complete dispersion due to the presence of weak aggregates that require minimal force to disrupt. Elliot and Stevenson (1989) also found that disruption was more rapid and complete with sandy soils than with heavy textured ones. Sandy soils tend to have weak structure due to high sand content, which has low surface area, no charge and no hydrogen bonding for formation of aggregates (REF).

Effectiveness of dispersing agents

Resin bags and sodium hexametaphosphate were effective in dispersing the sandy soil as complete dispersion was achieved. Both dispersing agents were however not effective in dispersing the red clayey soil. This was probably due to the strong interactions in the micro-aggregates such that there might be need for stronger forces to break down the aggregates.

Although the use of resin bags led to an increase in the dispersion of aggregates, it also led to a significant decrease in the amount of organic matter recovered. The use of resin bags could have caused further breakdown of the coarse organic matter or solubilisation of the organic matter. The material used to make the resin bags has a mesh size of about 150 µm such that some material may have been entrapped inside the bags and was difficult to wash out resulting in erroneous results and reducing the effectiveness of the regeneration of the resin bags.

There was no increase in dispersion caused by increasing the concentration of the hexametaphosphate from 0.5 to 2%. More effective dispersion might be achieved at higher concentrations of the salt, but hexametaphophate does not readily dissolve making it difficult to make higher concentrations. Sodium hexametaphosphate is likely to result in salt interacts with the fractions during mineralization making it unsuitable to use if incubation studies are to follow.

Effects of dispersing agent on organic C

The use of resin bags resulted in smaller amount of organic C in the coarse organic matter fractions and redistribution into finer fractions. The redistribution of organic matter among size fractions complicates efforts to selectively isolate organic matter fractions from specific sources in the soil confusing interpretation of results. The finer fractions were not analyzed in this preliminary test. Complete dispersion was not achieved for the clay soil such that the mineral fraction contained some micro-aggregates and a significant amount of organic C is found within micro-aggregates (Stevenson and Elliot, 1989).

Effect of soaking on improving soil dispersion

Soaking the soil before shaking led to an increase in the dispersion of aggregates (Table 2). Soaking did not affect the coarse organic matter fraction as it is not found in close association with the soil and hence is easy to disperse. There was a decrease in the amount of the coarse mineral fraction after soaking the soil as more aggregates were disrupted and the bonds in the aggregates weakened. The larger amounts of the mineral fractions in dispersion without soaking was due to the inclusion of aggregates, many aggregate classes have the same size range as sand (0.05-2mm). Increased dispersion after soaking led to an increase in the amount of the fraction less than 53um as the finer fractions that make up the aggregates were dispersed.

Effects of tillage treatments on the effectiveness of dispersion

The lack of differences in the sand size fractions organic matter contents between conventional tillage and clean ripping (Table 4) for the red clay soil could have been because no organic residues were added to the soil for both treatments. Clean ripping had higher organic matter contents in the finer fractions than conventional tillage probably due to aggregate disruption that occurs under conventional tillage causing higher organic matter decomposition. Mulch ripping had higher organic matter contents in the coarse and medium sand fractions than clean ripping because of organic residues that are added to the soil. Tied ridging had the highest amounts of organic matter probably because there was minimum tillage involved. The ridges were established at the onset of the experiment in 1988/89 season with opening of holes for planting such that there was minimum disruption of aggregates.

For the sandy soil bare fallow had lowest amounts of organic matter most probably because there were no organic residues added to the soil. The treatment involved annual ploughing without planting anything to the soil causing soil organic matter loss through runoff and erosion. Mulch ripping had the highest amounts of organic matter unlike the red clay where tied ridging had the highest amounts of organic matter. This was probably because of additions of organic residues under mulch ripping. The clay content of the sand was very low (<6%) such that there was no organic matter stabilisation between and within soil aggregates and the finer soil particles.

Conclusion

Of the methods tested using 0.5% sodium hexametaphosphate after soaking the soil would be the most suitable dispersing agent to use for getting high dispersion without altering organic matter distribution in the various size fractions for the red clayey soil and the sandy soil. This was so because increasing the concentration of sodium hexametaphosphate did not increase soil dispersion for the red clayey soil. Soaking the soil on the other hand resulted in an increase in disruption of aggregates by decreasing the mass of the mineral fraction by about 30%. Using resin bags resulted in low recoveries of the amount of organic C and mass of organic matter fractions compared with sodium hexametaphosphate and hence its selection.

Acknowledgements

Our research was sponsored by a grant from IFAD through TSBF. We would like to thank the engineers from the Institute of Agricultural Engineering for allowing us to work on the sites they established and giving us background information on the trials. These engineers include I. Nyagumbo, M. Munyati and G. Nehanda.

References

Blair, G. J., R. D. B. Lefroy, B. P. Singh and A. R. Till. 1997. Development and use of a carbon management index to monitor changes in soil C pool size and turnover rate. In: (eds G. Cadisch and K. E. Giller) Driven by nature: Plant litter quality and decomposition. CAB International.

Feller, C. and M. H. Beare. 1997. Physical control of soil organic matter dynamics in the tropics. Geoderma 79: 69-116.

Woomer, P. L., A. Martin, A. Albrecht, D. V. S. Resck and H. W. Scharpenseel. 1994. The importance and management of soil organic matter in the tropics. In: The Biological Management of Tropical Soil Fertility, (P. L. Woomer and M. J. Swift, eds), TSBF.

Table 1. A comparison of soil organic matter size fractions obtained using two dispersing agents, 2% sodium hexametaphosphate and resin bags

Treatment	Weight of size fraction (g/g soil)									
	212-2000 µm OM		212-2000µm Mineral		53-212 µm OM		53-212 µm Mineral		0-53 µm Mixed	
	HMP	Resin	HMP	Resin	HMP	Resin	HMP	Resin	HMP	Resin
Red Clayey										
Mulch	0.004	0.001	0.041	0.041	0.025	0.008	0.032	0.050	0.897	0.910
Conventional	0.003	0.001	0.038	0.034	0.019	0.005	0.041	0.062	0.895	0.897
Tied	0.006	0.003	0.035	0.036	0.023	0.012	0.052	0.054	0.888	0.896
Clean	0.003	0.001	0.039	0.039	0.018	0.007	0.046	0.070	0.882	0.884
t statistic	12.5		1.2		7.9		-5.1		-3.5	
Sandy										
Mulch	0.004	0.001	0.594	0.476	0.004	0.005	0.222	0.260	0.176	0.258
Conventional	0.002	0.001	0.647	0.462	0.002	0.001	0.213	0.262	0.138	0.174
Tied	0.004	0.001	0.616	0.547	0.002	0.002	0.204	0.238	0.172	0.212
Clean	0.003	0.001	0.591	0.457	0.002	0.002	0.249	0.276	0.155	0.262
t statistic	5.4		10.4		-2.6		-12.3		-5.9	

Table 2 A comparison of carbon content in organic matter size fractions obtained after using sodium hexametaphosphate (HMP) and resin bags as dispersing agents

Tillage treatment/ Soil type	Total C mg C g^{-1} soil	>212 µm OM mg C g^{-1} soil		53-212 µm OM mg C g^{-1} soil	
Red clay		HMP	Resin	HMP	Resin
Mulch	17.2	1.066	0.423	4.90	2.808
Conventional	14.9	1.023	0.484	4.418	1.857
Tied	20.4	2.319	0.959	5.016	2.517
Clean	16.8	1.065	0.480	4.201	1.761
Sandy soil					
Mulch	6.8	0.846	0.465	1.347	0.844
Conventional	4.2	0.376	0.216	0.362	0.281
Tied	4.8	1.032	0.470	0.397	0.563
Clean	4.6	0.941	0.444	0.651	0.454

Table 3 A comparison of soil organic matter size fractions obtained using 2% sodium hexametaphosphate before soaking and after soaking

	Weight of size fraction (g g^{-1} soil)									
Treatment	>212 µm OM		>212 µm Mineral		53-212 µm OM		53-212 µm Mineral		<53 µm Mixed	
	Unsoaked	Presoaked	Unsoaked	Presoaked	Unsoaked	Presoaked	Unsoaked	Presoaked	Unsoaked	Presoaked
Red Clayey										
Mulch	0.006	0.004	0.059	0.041	0.024	0.025	0.055	0.032	0.857	0.897
Conventional	0.003	0.003	0.050	0.038	0.16	0.019	0.065	0.041	0.855	0.895
Tied	0.007	0.006	0.055	0.035	0.023	0.032	0.076	0.052	0.841	0.888
Clean	0.004	0.004	0.058	0.039	0.014	0.018	0.067	0.046	0.858	0.882
t statistic	1.9		14.4		-0.7		0.0		-11.4	
Sandy										
Mulch	0.005	0.005	0.594	0.573	0.004	0.003	0.258	0.232	0.134	0.176
Conventional	0.002	0.002	0.647	0.634	0.002	0.001	0.236	0.219	0.180	0.138
Tied	0.004	0.004	0.619	0.616	0.001	0.001	0.246	0.224	0.152	0.172
Clean	0.004	0.003	0.591	0.586	0.003	0.002	0.256	0.240	0.129	0.155
t statistic	1.8		2.3		2.8		4.6		-0.9	

Table 4 A comparison of tillage effects on the amount of organic matter in a red clay soil from the Institute of Agricultural Engineering, Harare

Tillage treatment	Soil organic matter mg g^{-1} soil	Weight of organic matter fraction (mg g^{-1} soil)		
		212-2000 µm Coarse sand	53-212 µm Medium sand	20-53 µm Fine sand
Conventional tillage	14.9	2.65	3.64	5.46
Clean ripping	16.8	2.69	5.24	8.98
Mulch ripping	17.2	3.48	6.34	10.18
Tied ridging	20.4	6.08	12.28	11.36
Weedy fallow	27.9	22.46	19.72	17.76
SED		0.278	1.204	1.091

NB Fractions less than 20 µm (silt and clay) are not shown in the table because organic matter was not separated from the mineral particles.

Table 5 A comparison of tillage effects on the amount of organic matter in the sandy soil From Domboshawa Training Centre

Tillage practice	Soil organic matter mg g^{-1} soil	Weight of organic matter fraction (mg g^{-1} soil)		
		212-2000 μm Coarse sand	53-212 μm Medium sand	20-53 μm Fine sand
Bare fallow	2.2	0.32	0.60	0.58
Conventional tillage	4.2	1.54	1.48	1.70
Clean ripping	4.6	2.96	2.26	2.56
Tied ridging	4.8	3.78	1.54	2.12
Hand hoeing	6.0	3.40	2.10	3.08
Mulch ripping	6.8	4.68	4.26	3.16
Weedy fallow	11.3	3.34	18.26	4.98
SED		0.552	0.331	0.552

NB Fractions less than 20 μm (silt and clay) are not shown in the table because organic matter was not separated from the mineral particles.

Draft

Nitrogen mineralisation from aerobically and anaerobically treated cattle manures

J.K. Nzuma[1] and H. K. Murwira[2]
[1]Crop Nutrition Section, Chemistry & Soil Research Institute, Box CY 550 Causeway, Harare, Zimbabwe.
[2]T.S.B.F. Department of Soil Science, University of Zimbabwe, Box MP228, Mt Pleasant, Harare, Zimbabwe.

Summary

Short-term mineralisation-immobilisation turnover of N after amending soil with aerobic and anaerobic manures treated in April and July with or without straw was studied during a 77-day incubation period using the leaching tube method. The dynamics of N mineralisation were described by first order kinetics with high rate constants for anaerobic manures without straw treated in July. The decomposition of aerobic manures in soil followed a slow linear immobilisation pattern suggesting asynchrony of nutrient release and plant uptake. The course of N turnover for anaerobic manures suggested two phases, an initial exponential immobilisation phase followed by a slow linear re-mineralisation phase. It was concluded that in spite of the initial immobilisation period that occurred with anaerobic manures, the re-mineralisation that took place indicated that manure-N might be synchronised with crop demand in the short term.

Introduction

Different storage conditions influence both carbon and nitrogen turnover of the manures after application to soil. During aerobic composting organic materials of high stability are formed and the inorganic N can be low. Anaerobic decomposition can lead to the production of low-molecular compounds such as volatile fatty acids and high ammonium-N contents have been reported (Thomsen, 2000). The addition of anaerobically decomposed manure to soil has been found to immobilise N due to the presence of easily decomposable C sources as observed in the work of Bernal and Kirchmann, (1992), Flowers and Arnold (1983) and Sims, (1986), with pig slurry and Murwira, (1993) with cattle manure. The dynamics of C or N mineralisation of organic manures in soils have been described by first-order reaction kinetics (Chae and Tabatabai, 1986 or a set of first-order reactions (Gale and Gilmour, (1986).

In the present paper, we report the results of a study on N release patterns from aerobic and anaerobic manures treated in April and July with or without straw after application to a sandy soil The aim of the investigation was to establish possible differences in short-term N turnover rates in aerobic and anaerobic manures applied to soil and implications to the cropping system..

Materials and methods

Manures and soil used

Manures used in the study were obtained from four storage treatments namely pit manure (anaerobically decomposed) with or without straw; heap manure (aerobically composted) with or without straw. The manures had been composted in April 1999 and replicated in July 1999. Samples of manure were collected in October1999 and air dried then ground to pass a 2-mm sieve, analysed for organic C (Nelson and Sommers, 1982) total N using the Kjeldahl procedure (Bremner and Mulvaney, 1982).The chemical composition of these manures is presented in Table 1.

The experimental soil was collected from a site in Murewa. The soil was a deeply weathered and leached loamy sand with 4% clay, 4% silt, 92% sand and a pH of 4.5 ($CaCl_2$) classified as a Haplic Lixisol (FAO), Nyamapfene, (1991). The soil was air dried and allowed to pass through a 2mm sieve and analysed for organic C using the Walkely and Black Method (Nelson and Sommers, 1992) and total N using the Kjeldahl procedure (Bremner and Mulvaney, 1982).

Incubation procedure

The aerobic leaching tube mineralisation method (modified from Stanford and Smith, 1972) was used in this study. This method was employed to reduce the number of tubes that would be required if the static method was to be used. An added advantage of the leaching tube method is that it mimics the field situation where N is constantly removed from the soil crop system through crop uptake and leaching. The tubes can also be used over a long period without experiencing problems of accumulation of N and other toxic products of decomposition (Bremner, 1965; Stanford and Smith, 1972). One disadvantage of the leaching tube is that, it removes the soluble carbon, which drives the mineralisation process.

The leaching tubes consisted of a plastic transparent cylinder (200ml by volume) with a hole (0.5mm diameter) at the bottom. A narrow glass tubing (10cm long) was inserted at the base through the hole to allow drainage and secured with plasticine at the base. A glass wool 3cm thick was placed at the base of the tube to prevent movement of soil-manure particles from draining out of the tube.

Ten grams of acid washed sand was added on top of the glass wool before adding soil-manure mixture to ensure even distribution of suction. A further 10g of acid washed sand was added at the top of the soil-manure mixture to avoid movement of particles upon pouring leaching solution.

To reduce moisture loss, a pierced aluminum foil was placed on top of the tube covering it loosely. A mass of 100g of soil was placed in each glass jar. This was mixed homogeneously with 8 different manures applied at quantities equivalent to 60 kg N/ha and transferred into leaching tubes. A set of control tubes with 100g of soil only was added. All treatments were replicated 4 times. Moisture content was adjusted to 70% of water holding capacity (WHC) and the tubes were incubated in a constant temperature room at 25^{o}C.

Sampling

The tubes were leached at day 0 to remove background mineral N. They were then leached on day 3, 7 and every week thereafter for a period of 11 weeks. The tubes were leached with 100ml of a leaching solution in two 50ml aliquots and the leachates collected in conical flasks. The leaching solution contained 1mM $CaCl_2$, 1mM $MgSO_4$, 0.1 mM KH_2PO_4 and 0.9 mM KCI. At each leaching date, moisture content was adjusted to 70% of WHC.

Concentrations of mineral N (NH_4-N plus NO_3-N) in the leachates were measured immediately after sampling using micro Kjedhal N method. The mineralisation of manure nitrogen was determined by subtraction of the amount of inorganic nitrogen mineralized in the soil (control) from total inorganic N amounts mineralized in the soil-manure mixture.

Statistic analysis

Cumulative data on N mineralisation were fitted to a first order kinetic function using Genstat 5 procedures. Analysis of variance procedure using Mstat 1988 was used to measure the significance of net mineralisation during the incubation period.

Results

Chemical composition of manures

The chemical composition of manures is presented in Tables 1. Anaerobic manures were always high in total N concentrations. A greater proportion of the total N in these manures was present as inorganic N in the form of NH_4-N. Highest concentrations were observed for JP- manures. The C/N ratio for anaerobic manures was high, between 14 and 19 compared with 8 – 13 for aerobic manures.

Net N mineralisation

Net N mineralisation from manures (without soil) Fig. The course of mineralisation/immobilisation significantly differed ($P<0.05$) according to the different storage treatments applied to the manure samples prior to incubation. In general, there was also a significant month * straw interaction and straw * storage method interaction ($P<0.05$). Straw effect was significant ($P<0.05$) and amplified in anaerobic manures in July.

Anaerobic manures resulted in shorter periods of rapid initial immobilisation phase lasting between 4 and 5weeks Fig .1. In general, the immobilisation period was increased in manures with straw. Aerobically treated manures resulted in immobilisation, which lasted 7 weeks after incubation for manures with and without straw (Fig 1).

In terms of net N mineralisation, anaerobic manures had significantly higher net N mineralisation at 11 weeks after incubation than aerobic manures ($P<0.05$). July anaerobic manures were found to have significantly higher net N mineralisation than April manures. A release of 48 and 58 ugN^{-1}g soil of mineralisable N was observed from anaerobic manures with and without straw in July at 11 weeks. April anaerobic manures with and without straw released 25 and 30*ug* N g^{-1} soil of mineralisable N at 11 weeks. Anaerobic manures achieved a net N mineralisation of less than 20*ug* N g^{-1} soil for manures from this farm (Fig 1).

Cumulative N mineralisation

The cumulative N curves of aerobic and anaerobic manures were fitted to a first-order kinetic function with the rate constants describing the release of mineral N (Fig 2).

Mineralisation was expressed as a percentage of the amount of total manure-N added. After 77 days of incubation, N mineralised showed the following pattern:

JP- (30.65%) > JP+ (25.59%) > AP- (22.75%) > AP+ (22. 60%) > JH- = JH+ =AH- = AH+ (0.00%). The order of percentages of total N that was mineralised over 77 days of incubation followed that of the rate constants for the slow re-mineralisation phase High coefficients of determination were found (R2 = 0.939 -0.990). (Table 2).

In general, all aerobic manures followed a linear course for either nitrogen immobilisation or mineralisation which, lasted over the whole experimental period of 77 days. The rate constants were low for aerobic manures as shown in Table 2. The decomposition of anaerobic manures was characterised by two different phases, a rapid exponential initial immobilisation phase followed by a slow linear re-mineralisation phase.

The rate constants for the slow re-mineralisation phase exhibited the following pattern:

JP- (0.068 N day $^{-1}$) > JP+ (0.058 N day $^{-1}$) > AP- = AP+ (0.05 N day $^{-1}$) > JH- (0.038 N day $^{-1}$) > JH+ (0.028 N day $^{-1}$) > AH-= AH+ >0.00 N day $^{-1}$).

Discussion

Immobilisation phase

Initial immobilisation effects by anaerobic pretreated manures were observed in this study. The reason appeared to be three-fold; the high C/N ratio greater than 15 found in anaerobic manures which was similar to that reported by Bernal and Kirchmann, (1992) and Castellanos and Pratt, (1981). Secondly, high microbial activity, which causes a shift in microbial population from predominantly anaerobic bacteria resulting in a flush of readily available carbon and consequently more C utilisation for microbial proliferation (Thomsen and OsIen, 2000). Thirdly, the presence of energy-rich easily degradable C compounds by microorganisms such as volatile fatty acids (Spoelstra, 1979) (though not measured in this study), when a shift into aerobic conditions occurred. The work of Paul and Beauchamp, (1989) showed that volatile fatty acids in slurry can be oxidized within 4 days after amending soil with anaerobic manure together with a parallel immobilisation of NH_4-N. Earlier findings reported by Sims (1986) and Flowers and Arnold, (1983) found that up to 40% of NH_4-N in anaerobic manures can be immobilised.

The present data on prolonged periods of N immobilisation in soil with aerobic manures can be attributed to the stability of the organic materials in these manures. This is because easily decomposable organic compounds are respired during aerobic composting phase (Sana and Soliva, 1987). For example, water soluble and easily hydrolysable sugars are reduced during composting. Immobilisation of N was also possible with aerobic manures because a greater proportion of N was organically bound

These results imply that the application of aerobic manures to soil could induce N deficiency during rapid crop growth leading to depressed yields (Murwira and Kirchmann, 1993; Nyamangara et al., 1999; Paul and Beauchamp, 1994). These workers found N release from aerobic manures to be asynchronous with maize crop N requirements. The results from this study have also been demonstrated in the work of Thomsen, (2000), Hadas and Portnoy, (1994) and Hadas et al., (1996). Their findings showed low N mineralisation rates for composted manures as reported in this study.

Re- mineralisation phase

In spite of the initial immobilistion, which occurred in soil with anaerobic manures, re-mineralisation of the inorganic N, occurred with these manures achieving highest rate constants with July stored manures and subsequently more inorganic N was released than similar manures stored in April. These differences can be attributed to a decrease in mineralisation rates with length of storage as shown by Bernal et al., (1998) and more readily decomposable organic forms were converted to stable forms with prolonged duration of storage (Castellanos and Pratt, 1981; Chaney, Drinkwater and Pettygrove, 1992; Kirchmann, 1985). The re-mineralisation of N that occurred with anaerobic manures during the fifth and sixth weeks after incubation is in agreement with the work reported by Murwira and Kirchmann, (1993).

The results in this study contradict findings reported by Thomsen and Oslen, (2000) in which soils with anaerobic manures showed net immobilisation only after 266 days of incubation. Because of high microbial proliferation that occurs after application of anaerobic manures, these workers suggested that it might be more difficult to synchronise N release from anaerobic manures with crop N demand. However, in the present study, re-mineralisation of the inorganic N occurred close to the rapid crop growth stage between the fourth and sixth weeks after incubation. This implies that the release of N from these manures can be synchronised with crop N requirements.

Because of slow mineralisation rates found in soil after application of aerobic manures, crop yield potentials in the short term can be adversely affected. This might imply that aerobic manures are only beneficial to the crop in the subsequent years after application. (Tanner and Mugwira, 1984; Paul and Beauchamp, 1994).

Conclusion

Results showed significant variations in the decomposition of manures from different storage conditions. Differences in the rate constants between the manures reflected initial short term variations in the inorganic-N content of the readily decomposable fractions. Anaerobic manures with their high initial NH_4-N contents were found to have highest rate constants than aerobic manures.

The decomposition of anaerobic manures in soil almost always resulted in temporal initial immobilization. The immobilisation period was lengthened in manures with straw and by the age of manure owing to duration of storage. In spite of the initial immobilisation of the inorganic N that occurred in soil with these manures, re-mineralisation occurred close to the rapid crop growth stage reflecting that these manures may be synchronised with crop N requirements in the short term.

Little or no N was mineralised from aerobic manures. The implications are that these manures could be an inefficient source of fertiliser N for the crop. Though N released by these manures may be asynchronous with maize crop N requirements in the short term, the proportion of the N that still remains in organic bound form could be available for transformation in the residual years.

References

Bernal. P.M. and H. Kirchmann. 1992. Carbon and nitrogen mineralisation and ammonia volatilisation from fresh, aerobically and anaerobically treated pig manure during incubation Black et al., pp 1179-1237. Agronomy Journal. No. 9. Part 2. Madison, Wisconsin.

Bremner and Mulvaney, C. S. (1982). Nitrogen-Total. In Methods of Soil Analysis. Eds. A. L. Page et al., pp 595-634. Agronomy Journal. No. 9, Part 2, 2nd edition. Madison, Wisconsin.

Bremner, J.M. 1965. Inorganic forms of nitrogen. In C.A. Black (ed.) Methods of Soil Analysis. Part 2. Agronomy Journal. 9:1179-1237. Am. Soc. of Agron., Madison, Wisconsin.

Castellanos. J.Z. and P.F.Pratt. 1981. Mineralisation of manure nitrogen – Correlation with laboratory indexes. Soil Science Society of America Journal. 45:354-357.

Chae, Y.M. and M.A. Tabatabai. 1986. Mineralisation of nitrogen in soils amended with organic wastes. Journal of Environmental Quality. 15: 195-198.

Chaney, D.E, L.E. Drinkwater and G.S, Pettygrove. 1992. "Organic soil amendments and fertilisers". University of California. Oakland. California. USA.

Flowers, T.H. and P.W. Arnold. 1983. Immobilisation and mineralisation of nitrogen in soils incubated with pig slurry or ammonium sulphate. Soil Biology and Biochemistry. 15: 329-335.

Gale, P.M. and J.T. Gilmour. 1986. Carbon and nitrogen mineralisation kinetics for poultry litter. Journal of Environmental Quality. 15: 423-426.

Hadas, A. and R. Portnoy R (1994). Nitrogen carbon mineralisation rates of composted manures incubated in soil. Journal of Environmental Quality. 23:1184-1189.

Hidas, A. L. Kautsky, and R. Portnoy. 1996. Mineralisation of composted manure and microbial dynamics in soil as affected by long-term nitrogen management. Soil Biology and Biochemistry. 28:733-738.

Kirchmann, H and. E. Witter. 1989. Ammonia volatilisation during aerobic and anaerobic manure decomposition. Plant and Soil, 115: 35-41.

Kirchmann, H. 1985. Losses, plant uptake and utilisation of manure nitrogen during a production cycle. Acta Agriculture Scandinavia. Supplementum 24

Kirchman. H. and E. Witter. 1992. Composition of fresh, aerobic and anaerobic farm animal dungs, Bioresource Technology. 40:137-142.

Kirchmann, H. 1991. Carbon and nitrogen mineralisation of fresh, aerobic and anaerobic animal manures during incubation with soil. *Swedish Journal of Agricultural Research*. 21:165-173.

Kirchmann, H. and Bernal M.P. 1992. Organic waste treatment and carbon stabilisation efficiency. *Soil Biology and Biochemistry.* 29: 1747-1753.

MSTAT. 1988. Mstat microcomputer Statistical Program. Michigan State University, MI, USA.

Murwira H.K. and H. Kirchmann. 1993. Nitrogen dynamics and maize growth in a Zimbabwean sandy soil under manure fertilisation. Communications in Soil Science and Plant Analysis. 24:2 343- 2 359.

Nelson, D.N. and L.E. Sommers. 1982. Total-carbon, organic carbon and organic matter. pp. 323-363. In: Page AL et al., (eds). Methods of Soil Analysis. No. 9. 2nd edition. American Society of Agronomy, Madison, WI.

Nyamangara, J., M.I. Piha and H. Kirchmann. 1999. Interactions of aerobically decomposed cattle manure and nitrogen fertiliser applied to soil. Nutrient Cycling in Agroecosystems. 54:183-188.

Paul. J.W. and E.G. Beauchamp. 1994. Short-term nitrogen dynamics in soil amended with fresh and composted cattle manures. Canadian Journal of Soil Science.74:147-155.

Sims, J.T. 1986. Nitrogen transformations in a poultry manure amended soil: Temperature and moisture effects. Journal of Environmental Quality. 15:59-63.

Spoelstra, S.F. 1979. Volatile fatty acids in anaerobically stored piggery wastes. Netherlands Journal of Agricultural Science. 27: 60-66.

Tanner P. D. and Mugwira, L.M. 1984. Effectiveness of communal area manure as a source of nutrients for young maize plants. Zimbabwe Agricultural Journal. 81 (1): 31-35

Thomsen, I.K. 2000. C and N transformations in ^{15}N cross-labelled solid ruminant manure during anaerobic and aerobic storage. Bioresource Technology. 72: 267-274.

Thomsen, I.K. and J.E. Oslen. 2000. C and N mineralisation of composted and anaerobically stored ruminant manure in differently textured soils. Journal of Agricultural Science (Cambridge). 135:151-159.

Table 1. Some selected chemical properties of manures (N=3)

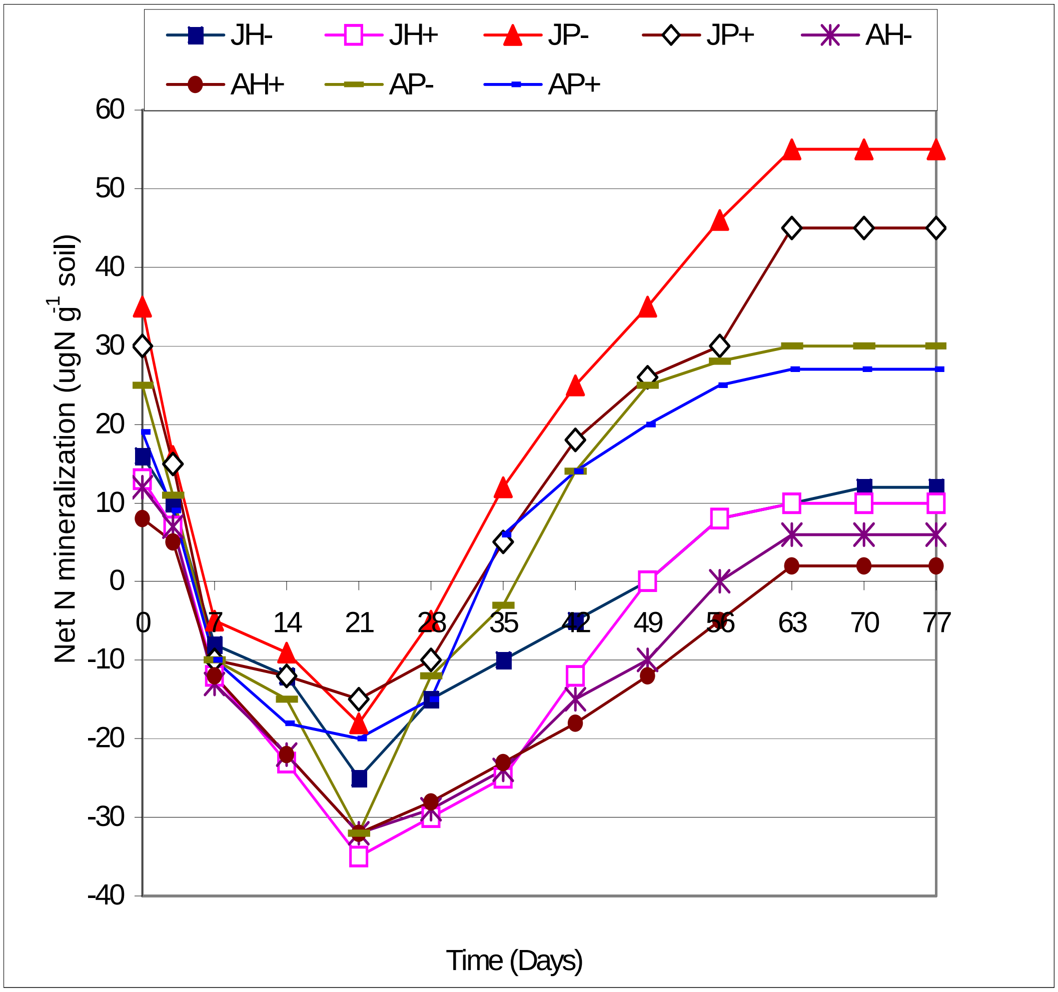
Storage Treatment	**Lignin (%)**	**Nitrogen (%)**	**Carbon (%)**	**NH_4-N (mg/kg)**	**C/N ratio**
JH-	1.32	1.00	9	560	9
JH+	5.31	0.90	7.8	400	8.6
JP-	6.41	1.86	25.5	285	14
JP+	10.92	1.48	27.8	255	18.9
AH-	0.41	0.70	7.2	335	10.2
AH+	1.68	0.62	7.8	320	12.5
AP-	14.59	1.22	18.6	230	15.2
AP+	8.37	1.14	19	202	16.6

J = July storage + = with straw H = heap manure (aerobic)
A =April storage - = without straw P = pit manure (anaerobic)

Table 2. N mineralisation/immobilisation kinetics in aerobic and anaerobic cattle manures mixed with soil; data obtained with a first order kinetic function.

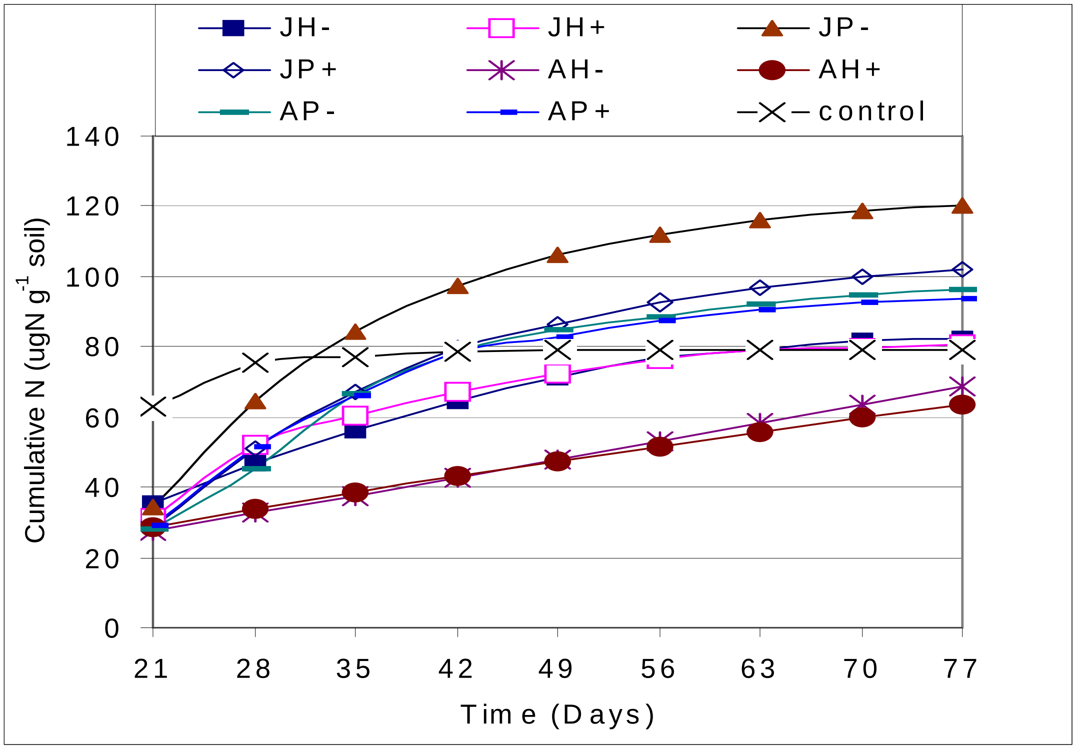
Manure storage treatment	Course of N turnover	N min. (%)	Rate constant (day $^{-1}$)	R^2
JH-	Linear immobilization	-	0.038	0.969
JH+	Linear immobilization	-	0.028	0.945
JP-	Exponential; Imm; linear min.	30.65	0.068	0.990
JP+	Exponential; Imm; linear min.	25.59	0.058	0.984
AH-	Linear immobilisation	-	0.000	0.939
AH+	Linear immobilisation	-	0.000	0.942
AP-	Exponential; Imm; linear min.	22.75	0.050	0.984
AP+	Exponential; Imm; linear min.	22.60	0.050	0.972

J = July storage + = with straw H = heap manure (aerobic)
A =April storage - = without straw P = pit manure (anaerobic)
Imm = immobilisation min. = mineralisation



J = July storage **+ = with straw** **H = heap manure (aerobic)**
A =April storage **- = without straw** **P = pit manure (anaerobic)**

Figure 1. Net N mineralisation/immobilisation of aerobic and anaerobic manures (n=3)
Data presented excludes soil.



J = July storage (aerobic) **+ = with straw** **H = heap manure**
A =April storage (anaerobic) **- = without straw** **P = pit manure**

Figure 2. Cumulative N mineralisation of aerobic and anaerobic manu. Lines represent the curve-fitting result, symbols are experimental data.

Draft

Influence of tillage management practices on organic carbon distribution in particle size fractions of a chromic luvisol and an areni-gleyic luvisol in Zimbabwe

P. P. Chivenge[1*], H. K. Murwira[1] and K. E. Giller[2]
[1]TSBF-CIAT, Box MP228, Mt. Pleasant, Harare, Zimbabwe.
[2]Professor-Plant Production Systems, Department of Plant Sciences, Wagenigen University, P. O. Box 430, 6700 AK Wagenigen, The Netherlands

Abstract
Long-term tillage effects on soil organic matter dynamics were evaluated for a Chromic Luvisol (red clay soil) and Areni-Gleyic Luvisol (sandy soil) in Zimbabwe. The soils had been under conventional tillage, mulch ripping, clean ripping and tied ridging for at least nine years. Clay soil had about three times more soil organic matter than the sandy soil because of better physical protection of organic matter. Conventional tillage caused the highest organic C decline of 47% and 61% for the red clay and sandy soils, respectively. The highest organic C content of 0.68% in the sandy soil was under mulch ripping whilst for the red clay soil tied ridging had the highest content of 2.04%. These values were, however low, when compared with the weedy fallow which was 1.13% and 2.79% total organic C soil for the sandy and red clay soils, respectively. This indicates preservation and lower losses of organic matter in the weedy fallow. Conventional tillage reduced organic C in the coarse fractions by up to 78% and 84% for the red clay and sandy soils, respectively. Clay size fractions were the most stable fractions because of physical protection from microbial attack and this was shown by their small responses to tillage. Most of the organic matter was associated with the finer fractions for the red clay soil while for the sandy soil the greater proportion of the organic matter was associated with the sand fractions.

Introduction
Conventional tillage mixes the surface soil horizon diluting the superficial organic layer and resulting in faster decomposition of organic matter compared with minimum tillage management practices. Conservation tillage results in higher organic matter contents due to reduced contact of added organic matter with the soil, reduced exposure of new soil surfaces and decreased soil erosion (Dalal, Henderson and Glasby, 1991). Cultivation disrupts aggregate-protected organic matter, that is, the heavier fractions thereby increasing its mineralization associated with greater short-term nutrient availability and loss from the soil (Hassink, 1995). Soil disturbance from tillage is a major cause of organic matter depletion and reduction in the number and stability of soil aggregates (Six *et al*., 2000). Soil organic C storage was 25% greater in the no tillage treatment than the conventional tillage (mouldboard ploughing) after nine years of continuous cultivation (Yang and Wander, 1999).

Removal of crop residues from the fields is known to enhance soil organic matter decline especially when coupled with conventional tillage (Yang and Wander, 1999). In most communal areas of Zimbabwe, crop residues are removed from the fields for use as animal feed, resulting in small inputs of organic matter. Practising conservation tillage and proper residue management can substantially increase long-term soil organic matter and crop production (Smith and Elliot, 1990). Leaving residues on the surface can increase crop productivity by conserving moisture and reducing soil erosion.

Conservation tillage practices can reduce soil organic matter loss compared with conventional tillage practices depending on the clay content of the soil (Janzen et al., 1998). There is more rapid SOM loss in coarse textured soils, characteristically found in the greater parts of the communal areas of Zimbabwe (Grant, 1981), where decomposition is enhanced by lack of physical protection of organic matter (Hassink, 1995). In fine textured soils, clay and silt sized particles with high surface activity may physically protect SOM from decomposition due to isolation within and between micro-aggregates (Franzluebbers et al., 1996). As a result clay soils tend to have higher SOM contents than sandy soils.

The objective of this study was to assess tillage effects on SOM content and SOM fractions on two different soil textures. It was hypothesised that minimum tillage practices would promote SOM build-up, especially the physically protected organic matter, compared with conventional tillage systems.

Materials and Methods

This experiment was done on the tillage experiments that were established in the 1988/89 season at the Institute of Agricultural Engineering (IAE) in Harare (17°45' S; 31°10'E) and Domboshawa Training Centre (DTC) (17°35' S; 31°10'E) approximately 40 km NE of Harare. The IAE site is on red clay soil derived from gabbro parent material and is classified as Rhodic Paleustalf (USDA), Chromic Luvisol (FAO) and Harare 5E.2 (Zimbabwe). The DTC site is on a sandy soil derived from granitic parent material classified as Udic Kandiustalf (USDA), Areni-Gleyic Luvisol (FAO) and Harare 6G.3 (Zimbabwe). The clay mineralogy for both locations is predominantly kaolinite. Both sites are found in Natural Region II (annual rainfall 800-1000 mm) with most of the rain falling between November and March.

The tillage treatments at the sites were as follows:

1. **Mulch Ripping**- rip-between-row into residues (tine into residues)
2. **Clean Ripping**- rip-between-row without residues (tine into bare soil)
3. **Conventional tillage**- annual ox ploughing (single furrow mouldboard plough and spike harrow)
4. **No-till tied ridging**- permanent crop ridges at 1 in 100 grades
5. **Hand hoeing**- digging out plant holes with a hand hoe without residues
6. **Bare fallow**- annual tractor disc plough and disc harrow, no crops are grown

At these sites there were annual fertiliser additions of 350 kg compound D (8% N, 14% P_2O_5, 7% K) and 250 kg ammonium nitrate (34.5% N) per hectare. The total amounts of nutrients added were 114 kg N, 50 kg P_2O_5 (22 kg P) and 25 kg K per hectare. Maize was planted as the test crop.

Soil samples were collected in October 1998 and passed through a 2 mm sieve. Fifty grams soil was shaken overnight in 200 ml of 2% sodium hexametaphosphate after soaking the soil overnight for 16 hours. Soil was wet sieved through a series of sieves to separate 212-2000 μm, 53-212 μm, 20-53 μm fractions followed by separation of organic and mineral fractions in each size fraction by swirling and floating of the organic matter in water. The 0-5 and 5-20 μm fractions were separated by the sedimentation method but were not separated for organic and mineral fractions. Carbon in the organic matter fractions and the mixed fractions was analysed using a Leco Carbon Analyser.

Statistical analysis was done using GENSTAT 5 for analysis of variance (ANOVA).

Results

Texture effects on organic matter content and distribution in size fractions

When comparing within tillage treatments, total organic C contents were higher in the red clay than the sandy soil (Tables 1 and 2). Total organic C was almost three times higher for the red clayey soil than the sandy soil for all the treatments. The weedy fallow had the highest total organic C contents for both the red clay and the sandy soil with the red clay soil having higher C contents (27.9 mg C g^{-1} soil) than the sandy soil (11.3 mg C g^{-1} soil) (Tables 1 and 2). Of the tillage treatments, tied ridging had the highest total organic C content with 20.4 mg C g^{-1} soil for the red clayey soil while for the sandy soil mulch ripping had the highest organic C content of 6.8 mg C g^{-1} soil. For both soils organic C content was lowest in the conventional tillage treatment with the red clay having 14.9 mg C g^{-1} soil and 4.2 mg C g^{-1} soil for the sandy soil.

Coarse sand organic matter content (212-2000 μm) was higher in the red clayey soil than the sandy soil for the conventional and tied ridging treatments where organic matter content was almost twice as high in the former than in the latter (Tables 1 and 2). Coarse organic matter content was similar in the red clay and the sandy soil for the other treatments. Organic matter content for the medium sand (53-212 μm) fraction was almost twice as high in the red clay soil than in the sandy soil except in the tied ridging treatment where organic matter was more than seven times as high in the clay soil than in the sandy soil. For the fine sand (20-53 μm) fraction, organic matter content was almost three times as high for the red clay soil than for the sandy soil. As the fraction size decreased the difference between the amount of organic matter in the sand and the clay soil increased with more organic matter being found in the clay soil.

Most of the organic matter was associated with the finer fractions for the red clay whilst for the sandy soil the greater proportion of the organic matter was associated with the coarse mineral (sand) particles. As the particle size decreased there was an increase in the amount of organic matter in the red clay soil whereas there was no difference in the amount of organic matter in the particle size fractions for the sandy soil (Tables 1 and 2).

Tillage effects on soil organic matter contents of the size fractions

For the red clayey soil clean ripping and conventional tillage had similar amounts of coarse and medium sand organic matter fractions although clean ripping had higher organic C content than conventional tillage (Table 1). In the fine sand fraction clean ripping had higher amounts of organic matter (10.1 mg g^{-1} soil) than conventional tillage (8.0 mg g^{-1} soil). Mulch ripping had higher total C, coarse and medium organic matter contents than clean ripping (Table 1). The fine sand associated organic matter content of conventional tillage was not significantly less than that of clean ripping. Of the tillage treatments, tied ridging had the highest organic C content and amount of sand organic matter fractions in the red clayey soil (Table 1).

Bare fallow resulted in the highest decline in soil organic matter content as indicated by the lowest total organic C content (2.2 mg C g^{-1} soil) and smaller amounts of organic matter in each of the size fractions (Table 2). Conventional tillage had low total organic C contents and low amounts of organic matter in the size fractions in the sandy soil. Mulch ripping had higher total organic C content and amounts of organic matter in the coarse- and medium-sand fractions than clean ripping (Table 2). However the amount of organic matter in the fine sand fraction was not significantly larger for the mulch ripping treatment compared with the clean ripping treatment. Total organic C and amounts of organic matter in the sand fractions for tied ridging were not significantly different from the clean ripping treatment except for the medium sand fraction where clean ripping (2.2 mg g^{-1} soil) had higher amounts of organic matter than tied ridging (1.5 mg g^{-1} soil) (Table 2). Hand hoeing had lower total organic C content and organic matter in the sand fractions than mulch ripping except for the fine sand fraction where there were no significant differences (Table 2).

For both soils the highest decline in organic matter under the different tillage treatments was in the coarse sand organic matter fraction when compared with the weedy fallow (Tables 1 and 2). With decrease in the organic matter size fraction there was a decrease in the magnitude of the difference in the amounts of the organic matter fractions under different tillage treatments when compared with the weedy fallow.

Tillage effects on organic C distribution in soil organic matter size fractions

Cultivation of soil at the IAE site led to a decrease in total organic C and organic C in the organic matter size fractions. All tillage treatments led to a decrease in organic C distributed in the size fractions when compared with the reference point, the weedy fallow. The coarse sand organic matter fraction (212-2000 μm) showed the highest decline in organic C after cultivation from 4.47 mg g^{-1} soil for the weedy fallow to as low as 0.97 mg C g^{-1} soil for conventional tillage (Table 3). The 0-5 μm fraction showed the lowest decline in organic C under all the tillage treatments. This was shown by the small margin of difference of organic C in the 0-5 μm size fractions under the tillage treatments compared with the weedy fallow. The smallest decline in organic C was under tied ridging in the 0-5 μm organic matter size fraction where there was no significant difference between organic C in the weedy fallow (23.5 mg C g^{-1} soil) and tied ridging (18.8 mg C g^{-1} soil).

Conventional tillage showed the highest decline in organic C in all the size fractions compared with the other tillage treatments and the weedy fallow. Tied ridging showed the least decline in organic C in all the organic matter size fractions (Table 3) as indicated by the high organic C in the organic matter size fractions compared with the other tillage treatments. Clean ripping had higher organic C contents in the organic matter size fractions except for the coarse sand organic matter fraction compared with conventional tillage but less than mulch ripping (Table 3).

At the Domboshawa site the bare fallow showed the highest decline in organic C in all the organic matter size fractions. This was more pronounced in the sand organic matter fractions where bare fallow had 0.05 mg C g^{-1} soil compared with 2.85 mg C g^{-1} soil for the weedy fallow (Table 4). In the clay size fraction bare fallow had 1.64 mg C g^{-1} soil while the weedy fallow had 4.37 mg C g^{-1} soil. Mulch ripping treatment had higher organic C contents in the organic matter size fractions than tied ridging. Mulch ripping had higher organic C (0.92 mg C g^{-1} soil) than hand hoeing (0.63 mg C g^{-1} soil) in the sand fractions (20-2000 μm) but had lower organic C contents in the finer fractions.

There was a differential treatment effect on total soil organic C and organic C in the organic matter size fractions caused by tillage for the two soils. Tied ridging had the highest organic C and C in the size fractions for the red clay soil (Table 3) and mulch ripping had the highest total organic C and C in the size fractions for the sandy soil (Table 4).

When organic C in the organic matter size fractions for both soils was totalled, recoveries of total organic C were not 100%. Higher organic C recoveries were obtained for the sandy soil than for the red clay soil. Organic C recoveries averaged 85% for the red clay soil (Table 3) and 95% for the sandy soil (Table 4).

Discussion

Effects of texture on organic matter content and distribution in size fractions

Total organic C was higher in the clay soil than in the sandy soil most likely due to lack of physical protection of organic matter from microbial attack in the sandy than in the clay soil, as well as larger residue inputs from roots due to greater productivity (Hassink, 1995; Hassink, 1996). The high clay content (~60% in the plough layer) in the clayey soil promotes formation of micro- and macro-aggregates which might physically protect soil organic matter from microbial decomposition and hence promote organic matter accumulation. This is unlike the sandy soil which has a low clay content (~5% in the plough layer) such that there is minimum aggregation and hence little organic matter accumulation. Hassink et al. (1997) observed a close relationship between silt and clay content, and organic C content of soil, with sandy soils having lower organic C in whole soil and fractions than clay soils.

The difference of organic matter contents of the coarse sand fractions for the red clay and the sandy soil was small but the differences increased as the fraction size decreased. Organic matter in the finer fractions is protected from microbial decomposition and hence the increase in the margin of the difference in organic matter content as the fraction size decreases for the red clay soil compared with the sandy soil, mainly due to the higher proportion of finer fractions in the clay soil. As a result of this much of the organic matter in the clayey soil tends to be associated with the finer particles.

Tillage effects on soil organic matter fractions and organic C in the organic matter fractions

Bare fallow involves ploughing of plots every year without planting anything and this enhances soil erosion resulting in soil organic matter loss. Ploughing the soil enhances organic matter decomposition by disrupting aggregate protected organic matter. This could have resulted in lower soil organic C and N when compared with the other tillage treatments. This supports the findings of Cambardella and Elliot (1994) who found that bare fallow soil had significantly less total organic C and N than mulch tillage and no-till soils. Cambardella and Elliot (1992) demonstrated that loss of coarse organic matter under a bare fallow treatment amounted to 70% of that of native grass over a period of twenty years.

For the red clayey soil clean ripping and conventional tillage had similar organic matter contents in the coarse and medium sand fractions probably because no residues were added to the soil in both treatments and hence they received similar and small amounts of organic inputs. In the fine sand, however, clean ripping had higher organic matter contents than conventional tillage probably due to reduced tillage for the clean ripping treatment such that there was reduced disruption of the soil resulting in reduced organic matter decline compared with conventional tillage. The higher coarse sand organic matter content in the mulch ripping treatment (34.8 mg g^{-1} soil) compared with 26.8 mg g^{-1} soil in the clean ripping treatment was probably because of organic residues that are added on the surface for the mulch treatment (Table 1). Total soil organic C and organic matter in the finer fractions was not significantly different for the two treatments probably because both treatments involve minimum tillage such that organic matter in the finer fractions is not affected by tillage. The two treatments are similar in terms of tillage intensity hence organic matter in the finer fractions was similar. Since much of the organic matter for the clay soil is associated with the finer fractions the difference in total organic C content of the two treatments was not significantly different. Tied ridging involves planting of maize on permanent ridges where tillage is reduced to opening of planting holes such that there is minimum soil disruption and hence greater organic matter accumulation.

Conventional tillage had low total organic C contents and organic C in the SOM fractions than conservation tillage practices mainly because of the high tillage intensity which enhance organic matter loss from the soil (Hassink, 1995) and small organic matter additions to the soil (Yang and Wander, 1999). Dalal et al. (1991) observed that in the top soil layers the interactive effects of zero tillage and returning of residues resulted in high organic C contents when compared with conventional tillage and zero tillage with residue burning. Work done by Arshad et al. (1990) showed that organic C and total N were 26% greater following 10 years of zero tillage compared with conventional tillage in the upper 7.5 cm of a silt loamy soil.

Lower organic matter contents for conventional tillage when compared with the conservation tillage treatments were most likely a result of aggregate formation and turnover processes. Conservation tillage practices allow for slow macroaggregate turnover resulting in the formation of fine particulate organic matter and the subsequent encapsulation of the fine particulate organic matter by mineral particle and microbial by-products to form stable microaggregates (Six et al., 2000). In contrast the turnover of macroaggregates in conventional tillage is fast, providing less opportunity for the formation of crop derived fine particulate organic matter and stable microaggregates (Six et al., 2000).

Mulch ripping had higher total organic C content (6.8 mg C g^{-1} soil) and organic matter in the coarse- (46.8 mg g^{-1} soil) and medium (42.6 mg g^{-1} soil) sand fractions than clean ripping for the sandy soil (Table 2). This was possibly due to the addition of organic residues under the mulch ripping treatment, which resulted in higher organic matter in the coarse- and medium sand fractions than clean ripping. This could have resulted in higher total organic matter under mulch ripping than clean ripping because much of the organic matter in the sandy soil is associated with sand particles and hence the larger sand size fraction organic matter with mulch ripping resulted in higher total organic matter content. Hand hoeing involves reduced tillage and hence had high organic matter contents although it was lower than mulch ripping.

There was a decrease in organic C in the organic matter fractions and total soil organic C for all the tillage treatments on the two soils compared with the weedy fallow (Tables 3 and 4). This was maybe because cultivation disrupts aggregate protected organic matter and enhances its decomposition. The largest decline of organic C in the organic matter fractions was in the sand fractions under conventional tillage, 4.47 mg C g^{-1} soil for the weedy fallow compared with 0.97 mg C g^{-1} soil for conventional tillage on the red clay soil (Table 3) and 2.85 mg C g^{-1} soil for the weedy fallow compared with 0.05 mg C g^{-1} soil for conventional tillage on the sandy soil (Table 4). This was probably because of the absence of the annual litter additions under conventional tillage compared with the weedy fallow. Conventional tillage also involves intensive cultivation of the soil promoting soil organic matter decomposition and subsequent loss from the system. For all the tillage treatments, however, the largest organic C decline occurred in the coarse organic matter fractions probably as a result of physical disintegration of soil aggregates associated with SOM decomposition and mineralization (Tiessen and Stewart, 1983). Tied ridging showed the least decline in organic C in the 0-5 μm fraction probably due to minimum tillage practised under tied ridging resulting in minimal disruption of aggregates.

These results confirm the findings of Cadisch et al. (1996) and Barrios, Buresh and Sprent (1996b), that coarse organic matter (light fraction) is an early indicator of changes in soil fertility and is the fraction most affected by cropping systems. Chan (1997); Hassink et al. (1997) also observed that the light fraction is lost more rapidly than other fractions. Under forest conditions, the light fraction was shown to be a strong short-term sink of N incorporating more than 50% of added N while the heavy (fine) fraction incorporated less than 5% after an 18 hour incubation (Compton and Boone, 2002). Work done by Lehmann et al. (1998), however, showed that short-term addition of Senna and Gliricidia leaves resulted in an increase in C and N in the silt and clay fractions.

Bare fallow involves annual ploughing without planting anything without any input additions. This induces soil erosion which is associated with soil organic matter loss showing a large decline in organic C in all the organic matter fractions in the bare fallow treatment compared with the weedy fallow and other treatments (Table 4). Unlike for the red clayey soil, mulch ripping had higher organic C in all the organic matter fractions than tied ridging probably due to low clay content such that there is little physical protection of organic matter for the sandy soil.

Results from this study indicate that there were higher soil organic matter losses under conventional tillage when compared with the other tillage treatments for both soils. This was maybe caused by the differing degrees of disruption of soil aggregates under the different management practices. Beare et al. (1994a) showed that after 13 years of conventional and no-tillage management resulted in 18% greater standing stock of soil organic C in the plough layer of no-tillage soil than conventional tillage soil. Beare et al. (1994b) also showed that the largest water stable aggregates were more abundant in the surface samples of no-till soil and that these aggregates were more stable and contained higher concentrations of C and N than did water stable aggregates under conventional tillage.

Tillage effects on maize yield and surface runoff

Soil organic matter results were supported by maize yields and runoff loss results that were observed in the same experiment. Conservation tillage practices had higher maize yields and lower runoff losses than conventional tillage although there were seasonal variations. The variations were mainly a result of differences in the rainy seasons with some seasons being wet while some seasons were dry (Figs 1 and 2).

In most seasons tied ridging gave higher grain yields for both soils because of the moisture benefits associated with tied ridging (Nehanda, 2000). The improvement in water use efficiency caused by tied ridging, which also had high organic matter contents could have possibly resulted in an increase in nutrient use efficiency resulting in higher yields. The higher maize yields under tied ridging were most likely associated with high root biomass additions to the soil and hence the high soil organic matter contents. In drier years conventional tillage gave higher yields because of less vigorous growth associated with crops under conventional tillage such that their moisture demands were lower. When however averaged across season, conventional tillage had the lowest maize yields. These results imply that conventional tillage causes faster soil degradation with increased soil organic matter decline, nutrient loss and susceptibility of soil to erosion, faster soil fertility decline and lower crop yields in the long run (Doran et al., 1987; Franzlubbers and Arshad, 1996; Feller and Beare, 1997). Higher grain yields were obtained for the red clay soil than the sandy soil due to the high water and nutrient holding capacity of the clay soil.

Conventional tillage resulted in higher surface runoff for both soils because tillage loosens soil making it prone to rain drop impact and detachment (Figs 3 and 4).

Conventional tillage had double surface runoff compared with the other tillage treatments while the other treatments had minimum surface runoff. The bare fallow treatment for sandy soil had the highest surface runoff losses because of the lack of a crop to cover the soil and protect the soil from being washed away from the soil surface. Surface runoff for the two soils was not different perhaps because the two sites receive similar rainfall. These results are similar to total C and organic C in the SOM fractions, where low organic C contents were observed under the bare fallow treatment and with high runoff losses, some of the organic could have been lost through erosion.

Conclusion

At the IAE site conventional tillage led to a high decline in total organic C content (14.9 mg C g^{-1} soil) and organic C in the organic matter fractions compared with tied ridging (27.9 mg C g^{-1} soil) that promoted organic matter accumulation. For the sandy soil there was higher total organic C and organic C in the organic matter fractions under the mulch ripping treatment while conventional tillage led to higher organic C degradation. This means that tied ridging conserves organic C for the red clayey soil while mulch ripping conserves organic C in the sandy soil compared with the other tillage treatments tested. Higher organic matter loss was observed for the sandy soil with up to 61% organic C decline following conversion from the weedy fallow to conventional tillage. This was much higher compared with 47% organic C decline under the same conversion for the clayey soil. This means that sandy soils degrade faster than clayey soils under the same management practices because they have lower capacity to protect soil organic matter. Higher crop yields on the red clay soil also resulted in higher organic matter additions to the soil through root biomass compared with the sandy soil.

Cultivation when compared to the weedy fallow results in the faster turnover and decline of organic matter especially in the coarse fractions. Conventional tillage resulted in faster losses of coarse organic matter than conservation tillage practices as there are no organic inputs and in the finer fractions because it does not allow for the formation of stable microaggregates.

References

Arshad, M. A., M. Schnitzer, D. A. Angers, and J. A. Ripmeester. 1990. Effects of till vs no-till on the quality of soil organic matter. Soil Biology and Biochemistry, 22: 595-599.

Barrios, E., R. J. Buresh, and J. I. Sprent. 1996b. Net nitrogen mineralization in density fractions of soil organic matter from maize and legume cropping systems. Soil Biology and Biochemistry 28:1459-1465.

Beare, M. H., P. F. Hendrix, and D. C. Coleman. 1994a. Water-stable aggregates and organic matter fractions in conventional and no-tillage soils. Soil Science Society of America Journal, 58:777-786.

Beare, M., M. L. Cabrera, H., P. F. Hendrix, and D. C. Coleman. 1994b. Aggregate-protected and unprotected pools of organic matter in conventional and no-tillage soils. Soil Science Society of America Journal, 58:787-795.

Cadisch G., H. Imhof, S. Urquiaga, R. M. Boddey, and K. E. Giller. 1996. Carbon turnover ($\delta^{13}C$) and nitrogen mineralization potential of particulate light soil organic matter after rainforest clearing. Soil Biology and Biochemistry, 28: 1555- 1567.

Cambardella, C. A. and E. T, Elliot. 1992. Particulate soil organic matter changes across a grassland cultivation sequence. Soil Science Society of America Journal, 56:777-783.

Cambardella, C. A. and E. T. Elliot. 1994. Carbon and nitrogen dynamics of soil organicmatter fractions from cultivated Grassland soils. Soil Science Society of America Journal, 58: 123-130.

Chan, K. Y. 1997. Consequences of changes in particulate organic carbon in vertisols under pasture and cropping. Soil Science Society of America Journal, 61: 1376-1382.

Compton, J. E., and R. D. Boone. 2002. Soil nitrogen transformations and the role of light fraction organic matter in forest soils. Soil Biology and Biochemistry, 34 (7): 933-943.

Dalal, R. C., P. A. Henderson, and J. M. Glasby. 1991. Organic matter and microbial biomass in a vertisol after 20yr of zero tillage. Soil Biology and Biochemistry, 23 (5): 435-441.

Doran, J. W., L. N. Mielke, and J. F. Power. 1987. Tillage/Residue management interactions with the soil environment, organic matter and nutrient cycling. In Cooley J. H. (ed.), Soil Organic Matter Dynamics and Soil Productivity. INTECOL Bulletin 1987:15.

Feller, C. and M. H. Beare. 1997. Physical control of soil organic matter dynamics in the tropics. Geoderma 79: 69-116.

Franzluebbers, A. J., and M. A. Arshad. 1996. Soil organic matter pools with conventional and zero tillage in a cold, semiarid climate. Soil and Tillage Research, 39: 1-11.
Grant, P. M. 1981. The fertility of sandy soils in peasant agriculture. Zimbabwe Agriculture Journal 78:169-175.
Hassink, J. 1995. Density fractions of soil macroorganic matter and microbial biomass as predictors of C and N mineralization. Soil Biology and Biochemistry, 27:1099-1108.
Hassink, J. 1996. Preservation of plant residues in soils differing in unsaturated protective capacity. Soil Science Society of America Journal, 60: 487-491.
Hassink, J., A. P. Whitmore, and J. Kubát. 1997. Size and density fractionation of soil organic matter and the physical capacity of soils to protect organic matter. European Journal of Agronomy, 7 (1-3): 189-199.
Janzen, H. H., C. A. Campbell, R. C. Izzaurralde, B. H. Ellert, N. Juma, W. B. McGill and R. B. Zentner. 1998. Soil and Tillage Research, 47:181-195.
Lehmann, J., N. Poidy, G. Schroth, and W. Zech. 1998. Short-term effects of soil amendment with tree legume biomass and nitrogen in particle size separates in Central Togo. Soil Biology and Biochemistry, 30 (12): 1545-1552.
Munyati, M. 2000 (unpublished). Conservation tillage for sustainable crop production. Results from on-station research in Natural Region II.
Nehanda, G. 2000. The effects of three animal-powered tillage systems on soil-plant-water relations and maize cropping in Zimbabwe. Dphil thesis, Department of Soil Science and Agricultural Engineering, Faculty of Agriculture, University of Zimbabwe.
Nyagumbo, I. 1998. Experiences with conservation tillage practices in southern and eastern Africa: A regional perspective. In: J. Benites, E. Chuma, R. Fowler, J. Kienzel, K. Molapong, J. Manu, I. Nyagumbo, K. Steiner and R. van Veenhuizen (eds), Conservation Tillage for Sustainable Agriculture: International Workshop, pp. 73-86, 22-27 June 1998, GTZ, Eschborn, Harare, Zimbabwe.
Nyagumbo, I. 2002. The effects of three tillage systems on seasonal water budgets and drainage of two Zimbabwean soils under maize. DPhil thesis, Department of Soil Science and Agricultural Engineering, Faculty of Agriculture, University of Zimbabwe.
Six J., E. T. Elliot and K. Paustian. 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no tillage agriculture. Soil Biology and Biochemistry 32: 2099-2103.
Smith J. L. and L. F. Elliot. 1990. Tillage and residue management effects on soil organic matter dynamics in semiarid regions. Advances in Soil Science 13: 69-88.
Tiessen H. and J. W. B. Stewart. 1983. Particle-size fractions and their use in studies of soil organic matter: II Cultivation effects on organic matter composition in size fractions. Soil Science Society of America Journal 47: 509-514.
Yang, X. M. and M. M. Wander. 1999. Tillage effects on soil organic carbon distribution and storage in a silt loam soil in Illinois. Soil and Tillage Research, 52:1-9.

Acknowledgements
Our research was sponsored by a grant from IFAD through TSBF. We would like to thank the engineers from the Institute of Agricultural Engineering for allowing us to work on the sites they established and giving us background information on the trials. These engineers include I. Nyagumbo, M. Munyati and G. Nehanda.

Figures 1 – 4 missing

Table 1 A comparison of tillage effects on organic matter in a red clay soil from the Institute of Agricultural Engineering, Harare

Tillage treatment	Total organic C mg g^{-1} soil	Weight of organic matter fractions (mg g^{-1} soil)		
		212-2000 µm Coarse sand	53-212 µm Medium sand	20-53 µm Fine sand
Conventional tillage	14.9	2.7	3.6	8.0
Clean ripping	16.8	2.6	5.2	10.1
Mulch ripping	17.2	3.4	6.3	10.2
Tied ridging	20.4	6.1	12.7	11.4
Weedy fallow	27.9	22.5	19.7	17.8
SED	0.6	0.278	1.204	1.091

(NB Fractions less than 20 µm (silt and clay) are not shown in the table because organic matter was not separated from the mineral particles.)

Table 2 A comparison of tillage effects on organic matter in the sandy soil from Domboshawa Training Centre

Tillage treatment	Total organic C mg g^{-1} soil	Weight of organic matter fractions (mg g^{-1} soil)		
		212-2000 µm Coarse sand	53-212 µm Medium sand	20-53 µm Fine sand
Bare fallow	2.2	0.23	0.6	0.6
Conventional tillage	4.2	1.7	1.5	1.7
Clean ripping	4.6	2.9	2.2	2.6
Tied ridging	4.8	3.1	1.5	2.1
Hand hoeing	6.0	3.4	2.1	3.1
Mulch ripping	6.8	4.7	4.3	3.6
Weedy fallow	11.3	10.5	8.6	6.9
SED	1.1	0.552	0.331	0.525

(NB Fractions less than 20 µm (silt and clay) are not shown in the table because organic matter was not separated from the mineral particles.)

Table 3 Tillage effects on organic carbon distribution in soil organic matter size fractions of a red clay soil in Harare

Tillage treatment	Organic C in SOM size fractions (mg C g^{-1} soil)							
	212-2000 µm coarse sand	53-212 µm Medium sand	20-53 µm Fine sand	5-20 µm Silt	0-5 µm Clay	Sum	Total measured	% Recovery
Conventional tillage	0.97	0.95	0.84	1.69	8.1	12.6	14.9	84.6
Clean ripping	1.05	1.21	0.96	1.90	8.7	13.8	16.8	82.1
Mulch ripping	1.04	1.34	1.00	2.09	9.0	14.5	17.2	84.3
Tied ridging	1.93	1.64	1.47	2.66	10.1	17.8	20.4	87.3
Weedy fallow	4.47	3.57	1.90	3.15	10.4	23.5	27.9	84.2
SED	0.167	0.187	0.091	0.118	0.242		0.6	

NB n=3 except for the weedy fallow where n=1

Table 4 Tillage effects on organic carbon distribution in soil organic matter size fractions of a sandy soil at Domboshawa Training Centre

Tillage treatment	Organic C in SOM size fractions (mg C g^{-1} soil)							
	212-2000 µm coarse sand	53-212 µm Medium sand	20-53 µm Fine sand	5-20 µm Silt	0-5 µm Clay	Sum	Total measured	% Recovery
Bare fallow	0.05	0.07	0.10	0.14	1.64	2.0	2.2	90.9
Conventional tillage	0.47	0.35	0.24	0.24	2.7	4.0	4.2	95.2
Clean ripping	0.53	0.37	0.33	0.34	3.0	4.5	4.6	97.8
Tied ridging	0.66	0.37	0.39	0.30	3.0	4.7	4.8	97.9
Hand hoeing	0.63	0.40	0.48	0.43	3.66	5.6	6.0	93.3
Mulch ripping	0.92	0.87	0.60	0.40	3.89	6.7	6.8	98.5
Weedy fallow	2.85	1.97	0.99	0.65	4.37	10.4	11.3	92.0
SED	0.183	0.112	0.075	0.131	0.657		1.1	

NB n=3 except for the weedy fallow where n=1

Draft

Towards Addressing Land Degradation in Ethiopian Highlands: Opportunities and Challenges

Tilahun Amede
TSBF-CIAT, AHI, Ethiopia

Introduction

Land resource degradation is one of the major threats to food security and natural resource base in Ethiopia. Hundreds of years of exploitve traditional land use, aggravated by high human and livestock population density have led to the extraction of the natural capital, which caused the farming of uncultivable sloppy lands and overexploitation of slowly renewable resources. The outcome is that half of the highlands are eroded, of which 15% are so seriously degraded that it will be difficult to reverse them to be agriculturally productive in the near future. In the mountainous highlands, there is a direct link between land-based resources and rural livelihoods. Decline in soil fertility as a result of land degradation decreases crop/livestock productivity and hence household income. Depleted soils commonly reduce payoffs to agricultural investments, as they rarely respond to external inputs, such as mineral fertilizers, and hence reduce the efficiency and return of fertilizer use. Degraded soils have also very poor water holding capacity partly because of low soil organic matter content that in turn reduce the fertilizer use efficiency. There have been various attempts to reduce land degradation in Ethiopia since the 1970s, through national campaigns on construction of terraces, project afforstation programmes and policy interventions. The objective of this paper is to review the various research/development experiences on integrated soil fertility management and synthesize the positive experiences augumented by the experiences of the African highlands initiative on integrated land management in Ethiopian Highlands. The paper will also suggest an outline that could be used by farmers, researchers and policy makers to reverse the alarming trend of land degradation in the mountainous highlands.

This work has consulted the available literature on land degradation and soil fertility management in Ethiopian highlands. While TSBF-CIAT/AHI has been working closely with the Ethiopian Agricultural Research Organisation (EARO) and the Buro of Agriculture, and conducting participatory research in two benchmark sites of the Ethiopian highlands on INRM issues, it became apparent that land degradation is the most fundamental threat for the Ethiopian Agriculture. Based on the systems intensification work that we have been conducting in the two benchmark sites of African highlands initiative, Areka and Ginchi, augmented by secondary data on relevant themes, the following approach was suggested to address land degradation in the country.

Root Causes of Land Degradation in the mountainous highlands

There are multiple factors that cause land degradation at short and long terms in the region. In Sub Saharan Africa, the major bio-physical agents of land degradation are water erosion, wind erosion and chemical degradation that affected soil loss by 47, 36 and 12%, respectively. Given the mountainous and sloppy landscapes, the major environmental factor that causes considerable soil and nutrient loss within a short period of time is water erosion followed by wind erosion. Most of the Wollo and Shewa highlands became erosion-prone due to high rainfall intensity accompanied by very steeply farmlands. Recent surveys showed that erosion effect is severe in high rainfall areas predominantly covered by nitisols and vertisols. In about 40% of the highlands, the erosion effect was so severe that active erosion was transformed to passive erosion, and hence there are rarely visible signs of sheet or rill erosion, but gullies and land slides. The hazards of erosion in the region was accelerated by socio-economic factors, namely absence of land ownership rights that discourage long term investments, population pressure, lack of alternative income generating options, and weak social capital that failed to protect communal grazing lands, up-slope forest covers and water resources.

Although the degree of soil erosion is highly related to the interaction of Wischmeier factors, the type of land use and management may have played an important role in the Ethiopian highlands. The contribution of different management factors towards land degradation in Africa is estimated to be 49%, 24%, 14%, 13% and 2% for overgrazing, agricultural activities, deforestation, overexploitation and industrial activities (Vanlauwe et al, 2002). The livestock sector is a very important component of the system both as an economic buffer in times of crop failure and economic crisis and as a supportive enterprise for crop production. There is a considerable concern, however, that the number of animals per household in Ethiopian highlands is much higher than the carrying capacity of land resources. Overgrazing due to very high livestock population density in the Amhara region is expected to contribute most to land degradation. For instance, the total annual feed available in the highlands is estimated to be about 9.1 million tones of biomass while the demand is about 21 million tones, double that of the carrying capacity of the land (Betru, 2002). Another very important factor that aggravated land degradation in the Ethiopian highlands is deforestation. The forest cover went down from 40% at the beginning of this century to less than 3% at present, due to ever-growing demand for wood products and very low commitment in planting trees mainly because of the prevailing nationalization of private woodlots in the 1970s and 1980s. Besides, a very high consumption of wood for fuel and housing, wood products, mainly charcoal, became a major cash generating activities in the country in recent years. Deforestation and overgrazing accelerated land degradation in many ways. Firstly a land without vegetative cover is easily susceptible to erosion, both wind and water, and hence causes a considerable nutrient movement. Secondly, a large amount of litter that could have contributed for maintaining soil organic matter and nutrient status is considerably reduced. Thirdly deforestation in the highlands caused lack of fuel wood, and hence farmers use manure and crop residue as cooking fuel, which otherwise could have been used for soil fertility replenishment.

Over-mining of land resources with out returning the basic nutrients to the soil is also an important factor that contributed most for soil fertility decline in the region. For instance, barley is the single dominant crop in the upper highlands of Wollo. The system has very low crop diversity with legume component of less than 3%. The system receives external inputs very rarely with a fertilizer rate of less than 5 kg/ha (Quinones et al., 1997), and the practice of applying this limited amount of mineral fertilizer is a recent practice. Data from the region on the amount of nutrients returned to the soil in comparison to the nutrients lost through removal of crop harvest showed that only 18, 60 and 7 % of nitrogen, phosphorus and potassium is returned to the soil, respectively (Sanchez et al., 1997). Hence there is an over mining of nutrients from the same rhizosphere for years and years.

Another cause of land degradation is lack of early awareness about land degradation by farmers, which is partly associated with the rural poverty. McDonagh, et al., (2001) reported that when farmers were asked to describe their indicators of soil erosion they stated gully/rill formation, exposed underground rocks, land slides, wash away of crops, shallowing of soils and siltation of the soil. Similarly farmers indicators of soil fertility decline include stunted crops, yellowing of crops, weed infestation, and change of soil color to red or grey. These are soil traits that appear in a much later stage of soil degradation, after the soil organic matter and nutrients of the soil are removed. If farmers respond to soil erosion at this stage, the probability of reversing the fertility status to its earlier value would be difficult.

Towards Integrated Soil Fertility Management

Application of small amounts of mineral fertilizer alone, as it has been practiced on the 0.5 ha demonstration plots by FAO and the ministry of Agriculture for years, did not improve crop productivity much. The failure of this mono-technology approach calls for an integrated nutrient management that suits local biophysical, social and economic realities. Integrated nutrient management technologies can be nutrient saving, such as in controlling erosion and recycling of crop residues, manure and other biomass, or nutrient adding, such as in applying mineral fertilizers and importing feed stuffs for livestock (Smaling and Braun, 1996).

The traditional field operation in the Ethiopian highlands, which could be characterized by multiple tillage, cereal-dominated cropping and very few perennial components in the system, is very erosive for soils and nutrients. Continual farming in the high lands with out considering conservation measures caused severe land degradation. FAO study in Zimbabwe showed that each hectare of well-managed maize growing land lost 10 tones of soil. Depleted soils commonly reduce payoffs to agricultural investments for various reasons. Degraded soils rarely respond to external inputs, such as mineral fertilizers, and hence reduce the efficiency and return of fertilizer use. Degraded soils have also very poor water holding capacity partly because of low soil organic matter content that in turn reduce the fertilizer use efficiency. Results from the dry regions of Niger, Sadore, showed that application of fertilizer increased the millet yield by 71% and also improved the water use efficiency by 70% (Bationo et al., 1993). Hence improved soil fertility enhances the water use efficiency of crops in drought prone areas. Low soil organic matter accompanied by low soil water content may also reduce the bio-chemical activity of the soil that may affect the above and below ground biodiversity of the system. Degraded soils have also low vegetative cover that may accelerate further soil loss and runoff.

The effect of soil fertility decline goes beyond nutrient and water losses. There are conviencing results showing that the incidence of some pests and disease is strongly associated with decline in soil fertility. Results from the Amhara and Tigrai region showed that the effect of the notorious parasitic weed, striga, on maize and sorghum was severe in nutrient depleted soil (Esilaba, et al, 2001). It was possible to decrease the population & the incidence of striga significantly by improving the fertility status of the soil through application of organic fertilizers. Similarly the incidence of root rots in beans, stem maggots in beans, take all in barely and wheat is associated with decline in soil fertility (Marschner, 1995). The positive effect of application of organic and inorganic fertilizer on the resistance of the host crop is mainly through improving the vigorosity of the plant at the early phonological stages.

Amede et al., (2001) outlined the need for a combination of measures to reverse the trend of soil fertility decline in the African highlands as presented in the following section.

1. Community-based soil and water conservation measures

There are about 40 different types of indigenous soil and water conservation practices in different parts of the Ethiopian highlands, ranging from narrow ditches on slopping fields in Wollo highlands to the most advanced & integrated conservation measures in Konso, Southern Ethiopia. However, those indigenous practices are location specific and variable in their effectiveness, and call for closer understanding before any attempt is done for scaling-up. However, there is a consensus among actors that any attempt to protect land resources and improve productivity in the sloppy highlands should integrate system-compatible soil conservation measures. Research conducted in Andit tid and Gununo showed that increasing the vegetation cover of the soil could decreases soil loss and runoff significantly (SCRP, 1996). In Andit tid, the amount of soil loss due to water erosion was 230 t/ha/year under hacked plots. However, it was possible to reduce the soil loss to 30 t/ha or less under crop covers or fallow grasslands (SCRP, 1996). When a cropland covered by crops or grasslands is compared to a frequently hacked farmland, run-off was reduced by about 90 and 100 % and soil loss by 68%, respectively. Hence soil nutrient loss and runoff could be minimized through increasing the frequency of crop cover, especially by those crops with mulching habits and higher leaf area indexs. Moreover, results from SCRP showed that perennial crops like enset and fruit trees or annuals with mulching and runner habits could reduce erosion effects significantly. Recent simulation modules in Northern Ethiopia showed that crop lands allocated for cereal crops like teff were very prone to erosion (Woldu, 2002), and the authors proposed that growing small seeded cereals, like teff, in sloppy farmlands should be discouraged.

There has been an attempt to control soil erosion and rehabilitate degraded lands through construction of farmland terraces in the Ethiopian Highlands starting from the early 1970s. The program was facilitated through the food-for-work scheme of the World Food Program, as a response to the frequent droughts of the 70s and 80s in Ethiopia. The program attempted to construct terraces on about 4 millions of hectares of farm land. In early 1990s, the annual physical construction of farmland terraces reached over 220,000 ha (Lakew, et al, 2000). However, as the campaign was trying to address the problem with out the full participation of the rural community, except selling labor, the farmers considered the activity as an external imposition and hence failed to develop sense of ownership. The consequence being that farmers failed to maintain the terraces and, in some case, farmers have destroyed the terraces for getting another round of payment. When farmers were asked to list the reasons for rejecting soil and water conservation technologies they listed five major driving forces (Amede, 2002, unpublished) namely high labor cost, decreased farm size due to terraces, its inconvenience during farm operations especially for U-turn of oxen plough, and inefficiency of the terraces to stop erosion as they were only physical structures without any biological component and technical follow-ups. By considering those farmers criteria and by adopting participatory planning and implementation approaches farmers have adopted and disseminated soil conservation technologies in one the African Highlands Initiative benchmark sites, Areka (Amede et al, 2001). The major driving force for the adoption of the technology was its integration with high value crops (e.g. bananas, hops) and fast growing drought resistant feeds (e.g. Elephant grass, pigeon pea) grown on the soil bunds. The sustainable integration soil & water conservation technologies also depend heavily on the effectiveness of by-laws that limit free grazing and free movement of animals especially during the dry spells. This requires the empowerment of the local and regional policies so as to facilitate the integration of natural resource management technologies to practices of local communities. Moreover, effective landscape management, in terms of controlling soil erosion, is possible only when there is a community collective action. Unless the landscape is treated as a single unit and involves all potential stakeholders, any individual intervention could provoke social conflicts. For instance, construction of soil conservation bunds and deforestation of forests at the upper slope of the Lushoto highlands, Tanzania, decreased the amount of water flew to the valley bottoms, and affected the vegetable production and income of other farmers.

2. Integrated Soil Fertility Management options

Building the organic matter of the soil and the nutrient stock in short period of time requires a systems approach. These include the combination of judicious use of mineral fertilizers, improved integration of crops and livestock, improved organic residue management through composting and application of farmyard manure, deliberate crop rotations, short term fallowing, cereal-legume intercropping and integration of green manures. Because of the inconsistent use of mineral fertilizers and the very limited returns of crop residues to the soil, most of the internal N cycling in small holder systems results from mineralization of soil organic N. Such process may contribute most of the N for the annual crops until the labile soil organic fraction (N-capital) are depleted (Sanchez et al., 1997).

Apart from the occasional application of small amounts of mineral fertilisers, all other organic resources form the principal means of increasing soil nutrient stocks and hence soil fertility restorers in small-scale farms. If these approaches are used in combination and appropriately, they could reverse the trend and consequently increase crop yields and, thereby alleviate food insecurity. However, the continued low yields are an indication of insufficient inputs and/or inappropriate use of these technologies. The majority of the small-scale farmers are still aggravating the soil/plant nutrient deficit through improper land management and over-mining of the nutrient pool. However, there is still an opportunity to replenish the soil nutrient pool using integrated approaches depending on the degree of soil degradation, the production system and the type of nutrient in deficit.

One potential source of organic fertilizer is farmyard manure. There is a large number of livestock in the Amhara region that could produce a considerable amount of manure to be used for soil fertility replenishment. However, there is a strong competition for manure use between soil fertility and its use as a cooking fuel. Recent survey in the upper central highlands of Ethiopia showed that more than 80% of the manure is used as a source of fuel. Only farmers with access to fuel wood could apply manure in their home steads. Experiences from Zimbabwe showed that most manures had very low nutrient content, N fertlizer equivalency values of less than 30%, sometimes with high initial quality that did not explain the quality of the manure at times of use (Murwira et al., 2002). This could be explained by the fact that most manures were not composed of pure dung but rather a mixture of dung and crop residues from the stall. Besides the quality the quantity of manure produced on-farm is limited. Sandford (1989) indicated that to produce sufficient manure for sustainable production of 1-3 tonnes/ha of maize it requires 10-40 ha of dry season grazing land and 3 to 10 of wet season Range land, which is beyond the capacity of Ethiopian farmers. Moreover, the potential of manure to sustain soil fertility status and productivity of crops is affected by the number and composition of animals, size and quality of the feed resources and manure management. Wet season manure has a higher nutrient content than dry season manure, and pit manure has a better quality than pilled manure. Similarly, Powell (1986) indicated that dry season manure had N-content of 6 g/kg compared with 18.9 g/kg for early rainy season manure when the feed quality is high.

Another potential organic source is crop residue. Returning crop residue to the soil, especially of legume origin, could replenish soil nutrients, like nitrogen. However, there is strong tradeoff for use of crop residue between soil fertility, animal feed and cooking fuel. In the upper Ethiopian highlands crop residues are used as a major source for dry season feed and supplementary for wet season feed. Hence little is remaining as a crop aftermath to the soil. Although legumes are known to add nitrogen & improve soil fertility, the frequency of legumes in the crop sequence in the upper highlands is less than 10%, which implies that the probability of growing legume on the same land is only once in ten years. The most reliable option to replenish soil fertility is, therefore, promoting integration of multipurpose legumes into the farming systems. Those legumes, especially those refereed as legume cover crops, could produce up to 10 ton/ha dry matter within four months, and are also fixing up to 120 kg N per season (Giller, 2002). Those high quality legumes adapted to the Ethiopian highlands include tephrosia, mucuna, crotalaria, canavalia, and vetch (Amede & Kirkby, 2002). However, despite a significant after effect of LCCs on the preceeding maize yield (up to 500% yield gain over the local management) farmers were reluctant to adopt the legume technology because of trade-off effects for food, feed and soil fertility purposes (Amede, unpublished data, 2002). In an attempt to understand factors affecting integration of soil improving legumes in to the farming systems of southern Ethiopia, Amede & Kirkby (2002) identified the most important socio-economic criteria of farmers namely, land productivity, farm size, land ownership, access to market and need for livestock feed. By considering the decision-making criteria of farmers on which legumes to integrate into their temporal & spatial niches of the system, it was possible to integrate the technology to about 10% of the partner farmers in southern Ethiopia.

Organic resources may provide multiple benefits through improving the structure of the soil, soil water holding capacity, biological activity of the soil and extended nutrient release, but it could be unwise to expect the organics to fulfil the plant demand for all basic nutrients. Most organic fertilizers contain very small quantities of some nutrients (e.g. P and Zn) to cover the full demand of the crop, and hence mineral fertiliser should supplement it. Combined application of organic fertilizers with small amount of mineral fertilizers was found to be promising route to improve the efficiency of mineral fertilizers in small holder farms. For instance, Nziguheba et al., (2002) indicated that organic resources enhanced the availability of P by a variety of mechanisms, including blocking of P-sorption sites and prevention of P fixation by stimulation of the microbial P uptake. Long term trials conducted in Kenya on organic and mineral fertiliser interaction also showed that maize grain yield was consistently higher for 20 years in plots fertilised with mineral NP combined with farmyard manure than plots with sole mineral NP or farmyard manure (S.M Nandwa, KARI, unpublished data 1997). Although most farmers are convinced of using farm-based organic fertilisers, they are challenged by questions like which organic residue is good for soil fertility, how to identify the quality of organic resource, how much to apply, when to apply, and what should be the ratio of organics to mineral fertilisers. This calls for development of decision support guides to support farmers' decision on resource allocation and management. Scientists from Tropical Soils Biology and Fertility Institute of CIAT developed decision guide to identify the quality of organic fertilisers based on the polyphenol, lignin and nutrient content as potential indicators (Palm et al., 1997). As those parameters demand laboratory facilities and intensive knowledge, Giller (2000) simplified the guide by translating it to local knowledge as highly astrigent test (high polyphenol content), fibrous leaves and stems (high lignin content) and green leaf colour (high N content) to make the guides usable to farmers.

In general, there is an increasing trend of mineral fertilizer use in the Ethiopian highlands over the past decades, and fertilizer imports into the country have increased from 47000 tonnes N & P in 1993 to

137 000 tones in 1996 (Quinones et al., 1997). It was mainly as a result of a strong campaign of Sasakawa-Global 2000 in collaboration with the Buro of Agriculture. However, there is a declining trend in fertilisers use in 2001/2002 due to increasing cost of fertilizers, lack of credit opportunities to resource poor farmers and low income return due to market problems.

3. Systems Approach to INRM

Sustainable rural development and natural resource management in the region demands an investment in and improvement of the natural capital, human capital and social capital. As the natural capital in the region had multiple problems that needs multiple solutions, there is a strong need for holistic approach to deliver options for clients of various socio-economic categories.

Given the complexity of the problem of land degradation, and its link to social, economical and policy dimensions, it requires a comprehensive approach that combines local and scientific knowledge through community participation, capacity building of the local actors through farmers participatory research and enhanced farmer innovation. This approach requires the full involvement of stakeholder at different levels to facilitate and integrate social, biophysical and policy components towards an improved natural resource management and sustainable livelihoods (Stroud, 2001). Watershed management as a unit of planning and change imposes the need for increased attention to issues of resource conservation and collective action by the community. The issues of land degradation may include afforstation of hillsides, water rehabilitation and/or harvesting and soil stabilization, soil fertility amendment through organic and mineral fertilizers and increasing vegetation cover by systematic use of the existing land and water resources. This could be achieved by working closely with communities and policy implementers in identifying and implementing possible solutions to address land degradation and other common landscape problems, like grazing land improvement, gully stabilization and by monitoring and documenting the processes for wider dissemination and coverage.

Some of the watershed conservation related solutions should be tried and implemented on specific test locations using farmers' own contribution and the INRM team's technical supervision. However, a wider application of these solutions to larger areas may require attracting additional funding investments from the district, donors or other NGOs in the area. The local village communities may also effect changes in the norms and rules governing the use of natural resources in their vicinity. Traditional rules and local by-laws (e.g. written and unwritten and called "afarsata" or awatcheyache) regarding the use and sharing of resources exist in most villages and these need to be identified and studied with a view to effect reform or renew their emphasis in the community. Integration of Agroforestry technologies in the farming systems of the Ethiopian highlands failed because of absence of national and/or local policies /by-laws that prohibit free grazing and movement of animals in the dry season. Experiences from the 1980s campaign of 'Green Campaign' in Ethiopia also showed that it is almost impossible to address the issue of land degradation without the full involvement and commitment of the local community. The local by-laws in resource arrangement and use should be facilitated and supported, as the rules and regulations at the local level could be implemented effectively through elders and respected members of the community with tolerance and respect. There may be a church and/or witchcraft dimensions to these, and there may be changes over time that might help to understand why people are doing what they are doing. In addition, the influence of national and regional policies on local resource management should be understood. These will form an important subject of community wide discussion and deliberation (Stroud, 2001). The current undertaking of soil and water conservation practices through voluntary participation campaign of the community in the northern Ethiopian Highlands is one positive step forward for initiating collective action.

References

Amede, Tilahun; Endrias Geta and Takele Belachew, 2001. Reversing soil degradation in Ethiopian Highlands. Managing African Soils No. 23. IIED-London.

Amede, Tilahun and R. Kirkby , 2002. Guidelines for Integration of Legume Cover Crops into the Farming Systems of East African Highlands. Proceedings of TSBf – African soils network (Afnet) 8th workshop, 7-10 May, 2001 Arusha, Tanzania. In press.

Aweto, A.O., Obe, O. and Ayanninyi, O.O. 1992. Effects of shifting and continuous *cultivation* of cassava (*Manihot esculenta*) inter-cropped with maize (*Zea mays*) on a forest Alfisol in southwestern Nigeria. *Journal of Agricultural Science*, Cambridge, 118, 195 - 198.

Bationo, A., C.B. Christianson, and M.C. Klaij, 1993. The effect of crop residue and fertilizer use on pearl millet yield in Niger. Fert. Res. 34:251-258.

Giller, K.E. 2000. Translating science into action for agricultural development in the tropics: an example from decomposition studies. Applied soil ecology 14: 1-3.

Giller, K.E. 2002. Targeting management of organic resources and mineral fertilizers. Can we match scientists fantasies with farmers' realities ? p: 155-171. In: Vanlauwe, B., J. Diels, N. Sanginga and R. Merckx, 2002. Integrated plant nutrient management in Sub-Saharan Africa: From Concept to practice. CABI International UK, 2002. 352 p.

Jama, B., Buresh, R.J., and Place, F.M. 1998. Sesbania tree fallows on phosphorus deficient sites: Maize yield and financial benefits. *Agronomy Journal* 90 (6), 717 – 726.

Marschner, H. !995. Mineral nutrition of higher plants. Academic press, 2nd edition. 889 pp.

McDonagh, J. Y. Lu and O. Semalulu, 2001. Bridging research and development in soil fertility management: DFID NRSP programme, Uganda. Unpublished.

Murwira, H.K., P. Mutuo, N. Nhamo, A.E. Marandu, R. Rabeson, M. Mwale and C.A. Palm, 2002. Fertilizer equivalency values of organic materials of differing quality. In: Vanlauwe, B., J. Diels, N. Sanginga and R. Merckx, 2002. Integrated plant nutrient management in Sub-Saharan Africa: From Concept to practice. CABI International UK, 2002. 352 p.

Palm, C.A., R.K. Myres, S.M. Nandwa, 1997. Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. 1997. In: Replenishing soil fertility in Africa. SSSA special publication number 51, 193-218.

Powell, J.M. , 1986. Manure for cropping: A case study from central Nigeria. Exp. Agric. 22:15-24.

Quinones, M., N.E. Borlaug, and C.R. Dowswell, 1997. A fertilizer-based green revolution for Africa: In: Replenishing soil fertility in Africa. SSSA special publication number 51, 81-96.

Sanchez, P.A., K.D. Shepherd, M.J. Soule, F.M. Place, R.J. Buresh, AM. N.Izac, A.U. Mokwuyne, F.R. Kwesiga, C.G. Ndiritu, P.L. Woomer, 1997. Soil fertility replenishment in Africa: An investment in natural resource capital. In: Replenishing soil fertility in Africa. SSSA special publication number 51, 1-46.

Sandford, S.G., 1989. Crop/ Livestock interactions. P. 169-182. In: Soil, crop, and water management systems for rain fed agriculture in the Sudano-Sahalian zone. Int. Crops Res. For the Semi arid tropics, Patancheru, India.

Smaling, E.M.A and A.R. Braun, 1996. Soil fertility research in sub Saharan Africa. New dimensions, New challenges. Commun. Soil Sci. Plant Anal.,27:365-386.

Soil Conservation Research Program (SCRP), 1996. Data base report (1982-1993), Series II: Gununo Research Unit. University of Berne, Berne.

Stroud, A. 2001. Sustainable INRM in practice, Ethiopia. AHI phase III planning report. Kampala, Unpublished.

World Reference Base for Soil Resources, 1998. Food and Agriculture Organization of the United Nations. World Soil Resources reports No. 84, Rome. pp 88.

Vanlauwe, B., J. Diels, N. Sanginga and R. Merckx, 2002. Integrated plant nutrient management in Sub-Saharan Africa: From Concept to practice. CABI International UK, 2002. 352 p.