Output 1. Biophysical and socioeconomic constraints to integrated soil fertility management (ISFM) identified and knowledge on soil processes improved

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BNF: A key input to integrated soil fertility management in the tropics

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Abbreviations and acronyms: AABNF, african association for biological nitrogen fixation; AfNet, african network for soil biology and fertility; BNF, biological nitrogen fixation; CGIAR, consultative group on international agricultural research; CIAT, centro internacional de agricultura tropical; CNDC, combating nutrient depletion consortium; CP, challenge program; DSSAT, decision support system for agrotechnology transfer; ECABREN, eastern and central africa bean research network; FPR, farmer participatory research; FYM, farm yard manure; GIS, geographical information systems; ICARDA; ICRAF, international center for research on agroforestry; ICRISAT, international crops research institute for the semiarid tropics; IITA, international institute for tropical agriculture; INM, integrated nutrient management; INRM, integrated natural resource management; ISFM, integrated soil fertility management; MIS, integrated management of soils; NARS, national agricultural research systems; NGOs, nongovernamental organizations; OM, organic matter; ORD, organic resource database; PABRA, pan-african bean research alliance; PRGA, participatory research and gender analysis; Profrijol, Regional bean network for central America, Caribbean and Mexico; QTL, quantitative trait loci; SROs, specialized research organizations; SWNM, soil, water and nutrient management; TSBF, tropical soil biology and fertility; TSP, triple super phosphate; UNDP, united nations development program.

Abstract

It is widely recognized that biological nitrogen fixation (BNF) by the legume-rhizobium symbiosis is an important component of productivity in tropical agriculture, especially in farmland which is marginal either in terms of distance from the markets, or small farm size and poverty of the farmers.

This position paper starts out by describing, the importance of BNF to tropical agriculture, the evolution of BNF paradigms, progress in creation of strategic alliances to combat soil fertility degradation, and past accomplishments of BNF-related research at CIAT-TSBF in collaboration with partners. Based on lessons learned, the paper suggests that BNF research should not be conducted in isolation but that a holistic-multidisciplinary-systems approach is needed to integrate BNF-efficient and stress adapted legumes into smallholder systems of the tropics. The paper proposes a number of research and development priorities for the BNF-CP to address for achieving improved contributions of BNF through integrated soil fertility management (ISFM) in the tropics. ISFM is the adoption of a holistic approach to soil fertility that embraces the full range of driving factors and consequences – biological, physical, chemical, social, economic and political – of soil degradation.

BNF research on common bean and tropical forage legumes at CIAT started in the 1970s. CIAT maintains a collection of 5,628 *Rhizobium* strains. Lessons with BNF research in bean can be summarized as follows. BNF has not been a panacea, neither on the side of strain selection nor breeding of the host, but modest progress has been registered. On the one hand, even if response to inoculation is not dramatic, the technology is so inexpensive that any response at all is economically viable. On the other hand, the environment is at least as limiting on BNF as is the strain and the host. Therefore the benefits of BNF are best expressed in the context of an agronomic management system that addresses other components of the crop, especially phosphorus supply, drought stress and not infrequently starter N. Selection for BNF capacity under physiological stress has revealed genotypes (and possibly genetic systems) that are worth exploiting more fully and which could hold keys to broader progress. Research efforts on BNF in tropical forage legumes indicated that the main constraints to the widespread adoption of forage legumes include a lack of legume persistence, the presence of anti-quality factors such as tannins, variable *Bradyrhizobium* requirements and a lack of acceptability by farmers. The main problem identified is that there is not enough work done on participatory evaluation of legumes with farmers to identify their criteria for acceptability and feed this information forward into germplasm screening. What is needed here is better collaboration among stakeholders to really get legume adoption under way in the tropics.

In other research programmes, it was confirmed that there is little scope for using legumes as an entry point to address soil fertility decline, but that there are various opportunities using multipurpose germplasm to indirectly improve the soil fertility status while providing the farmer with immediate products.

TSBF researchers in collaboration with partners made substantial progress in creating an organic resource database and using it to construct a decision support system (DSS) for organic matter management based on organic resource quality. Analysis of organic resource data indicated a hierarchical set of critical values of nitrogen, lignin and polyphenol content for predicting the "fertilizer equivalence" of organic inputs. This decision tree provides farmers with guidelines for appropriate use of organic materials for soil fertility improvement. On-going TSBF network experiments are now addressing the organic/inorganic nutrient interactions to allow the refinement of the recommendations to farmers. TSBF and CIAT with a wide range of partners are also developing methods for disseminating ISFM options through processes of interactive learning and evaluation among farmers, extensionists and researchers.

BNF-related research should proceed along the process-component-systems continuum and lead to demand-driven, on-farm problem-solving. Addressing farmers' problems in a systems context generates management options better suited to their local needs. Developing adoptable legume-BNF technologies to combat soil fertility degradation remains to be a major challenge. Research and development efforts are needed to integrate BNF efficient and stress-adapted grain and forage legume germplasm into production systems to intensify food and feed systems of the tropics. Several key interventions are needed to achieve greater impact of legume-BNF technologies to improve livelihoods of rural poor. These include: (a) integration of stress-adapted, BNF-efficient, grain and forage legume cultivars in rotational and mixed cropping systems, (b) development of management options aiming at optimal use of the legume-N in combination with strategic applications of mineral fertilizers to maximize nutrient cycling and soil organic matter replenishment, (c) adoptable strategies of soil and water conservation, (d) integrated pest/disease/weed management through the use of biotic stress resistant germplasm with minimum pesticide/herbicide applications, (e) marketing strategies that are economically efficient, and (f) development of an appropriate policy and institutional environment that provides incentives to farmers to adopt legume-based BNF technologies.

1. Introduction

It is widely recognized that biological nitrogen fixation (BNF) by the legume-rhizobium symbiosis is an important component of productivity in tropical agriculture, especially in farmland which is marginal either in terms of distance from the markets, or small farm size and the poverty of the farmers (Giller, 2001). In such resource-poor, smallholder systems the application of large quantities of inorganic fertilizers such as urea is not economically feasible. The use of management techniques that increase the contribution of N to the system through the legume-rhizobium symbiosis, would improve crop-livestock production levels and their stability. A major challenge for BNF research is developing strategies to integrate BNF-efficient and stress-adapted legumes (grain/forage/greenmanure/cover/fallow) into local cropping systems for the crucial transition of smallholders in the tropics from subsistence agriculture to mixed-enterprise, market-oriented production systems because it is only through this development that spiraling declines in poverty, food insecurity and land degradation may be addressed.

The central issues of the BNF-CP are: (1) managing factors that determine integration of legumes into agricultural systems; and (2) realizing the benefits of legumes through effective BNF. Developing adoptable legume-BNF technologies could markedly improve livelihoods of rural poor in a variety of ways. Legumes can contribute directly to food security and human and animal nutrition. They can also contribute to income generation where markets for legumes exist or where enhanced soil fertility via BNF permits production of high value commercial crops. When legumes substitute for purchased fertilizer inputs, households can save scarce cash. Finally, for both economic and socio-cultural reasons, legumes may be particularly suited to reaching women and the poor. Because of their critical role in food production, especially legume production, women should be at the core of any strategies to ameliorate soil fertility via BNF. This is especially important in sub-Saharan Africa, where women produce up to 70-80% of the domestic food supply, and they also provide, on average, 46% of the agricultural labor (Gladwin et al. 1997). Realizing these livelihoods gains, especially for the poor and marginalized, is the ultimate objective of the BNF-Challenge Program (CP).

Although significant advances were made in BNF research during 20th century, impact of this research to improve productivity of smallholdings in the tropics through N input has been small, e.g., less than 5 kg N per hectare per year (Giller, 2001). Recently, Giller (2001) has analysed the likely impact of future BNF research. He put forward the view that the amounts of BNF in tropical agriculture could be improved enormously if current understanding was put to more effective use via simple agronomic practices on-farm. Beyond this the most rapid additional gains are likely to come from adapting legume germplasm to different agroecological niches in cropping systems. Other approaches such as genetic engineering are likely to take much longer to yield benefits.

This position paper starts out by describing the evolution of BNF paradigms, importance of legume-BNF to tropical agriculture, progress in creation of strategic alliances to combat soil fertility degradation, and past accomplishments of BNF-related research at CIAT-TSBF. Based on lessons learned, the paper suggests that BNF research should not be conducted in isolation but that a multidisciplinary systems approach is needed to integrate BNF-efficient and stress adapted legumes into smallholder systems of the tropics. The paper proposes a number of research needs and challenges for BNF-CP to address for achieving improved BNF through integrated soil fertility management (ISFM) in the tropics.

1.1 Importance of legume-BNF to tropical agriculture and soil fertility

Various BNF technologies addressinng the problems of food insecurity, poverty and land degradation can be identified with various potentials for BNF (Table 1). Legume-rhizobium symbiosis can sustain tropical agriculture at moderate levels of output, provided all environmental constraints to the proper functioning of the symbiosis have been alleviated (see later). Legumes can accumulate up to 300 kg N ha^{-1} in 100 to 150 days in the tropics (Table 1). Rhizobial inoculation in the tropics can enhance yield of grain legumes when phosphorus availability in soil is not a major limitation.

Legume-cereal intercrops or rotations are widely practiced in the tropics to minimize the risk of crop failure and to provide households with improved diets. Traditionally, the main contribution of BNF in these systems is to improve household food security and human nutrition rather than improved soil fertility. Table 1, however, indicates various other niches for legumes in croppnig systems, each with their own specific contributions to improvement of food security, or land restoration.

1.2 Evolution of BNF paradigms

The African Association of biological nitrogen fixation (AABNF, 2001) summarized the first paradigm for BNF research of the 20th century as *"the upper limits of BNF may be steadily increased by the collection and evaluation of ever-more effective N_2-fixing micro organisms and their hosts because the distribution of this elite germless will necessarily accrue benefits following their introduction to production systems"*. This paradigm during the 20th century faced a major challenge that greater knowledge over time was not accompanied by improved BNF in the field. The widening gap between scientific advance of BNF and opportunities realized from their application is leading to the evolution of a new paradigm for BNF research. The 21st Century Paradigm designed by AABNF for greater BNF impacts may be summarized as *"research in biological nitrogen fixation must be nested into larger understandings of system nitrogen dynamics and land management goals before the comparative benefits of N_2-fixation may be realistically appraised and understood by society-as-a-whole"*. It is critical to note that this assumption does not reduce the importance of nitrogen-fixing organisms and their products, but rather repositions them from a central auto ecological focus into a more integrated component of a larger, more complex task. The rationale behind this new paradigm is that it is not biologically-fixed nitrogen alone which sets the standard for successful contribution to social needs, but rather the products realized from more resilient and productive ecosystems that are strengthened through BNF.

1.3 TSBF-CIAT

The former Tropical Soil Biology and Fertility Programme (TSBF), an international institution devoted to integrated soil fertility management (ISFM) research, has joined with the International Center for Tropical Agriculture to form the TSBF Institute of CIAT. This brings together TSBF's expertise in ISFM with that of CIAT in soils and land management as well as the complementary areas of germplasm improvement, pest management, GIS and participatory research. This merger builds on the strong collaboration between CIAT and TSBF in soil fertility research in East Africa that has developed within the CGIAR Systemwide Programme on Soil Water and Nutrient Management (SWNM) for which CIAT is the convening centre.

ISFM is the adoption of a holistic approach to soil fertility that embraces the full range of driving factors and consequences – biological, physical, chemical, social, economic and political – of soil degradation. There is a strong emphasis in ISFM research on understanding and seeking to manage the processes that contribute to change. The emergence of this paradigm, very closely related to the wider concepts of Integrated Natural Resource Management (INRM), represents a very significant step beyond the earlier, narrower, nutrient replenishment approach to soil fertility enhancement.

Table 1. BNF interventions for income generation and food security, their social benefits, target systems and potential. Adapted from AABNF (2001).

BNF Interventions	Social benefits (0, 1 to 5)					Land Use system	*Geo. range*	Pot. BNF (kg/ha)	Current BNF (kg/ha)	Pot. Impact	Specifics
	Income generation	Food security	Land cons./rest	*C*	*Bio D*						
Crop related											
Soybean rotation (Parasitic weed supp.)	5	2	3	1	1	S to L	SA to H	150	< 50	high	Germplasm imp. Agron. Practices ***P inputs*** Screening germ. Marketing Post -harvest
Cowpea rotation/int	3	4	3	1	3		SA to SH	70-80	<40	high	
Groundnut rot/int	3	3	2	0	1	S to L	SA to H	80	~ 60	high	
Pigeon pea int.	2	3	4	2	1	S	SA to SH	150	<50	Med-high	
Phaseolus beans int.	3	4	0	0	2	S	SA to SH (MA/HA)	70	<10	med	
Livestock related											
Woody fodder banks	4	2	4	3	2	S	MA to HA	300	30-50	high	Calliandra etc.
Herbaceous fodder banks	3	2	3	2	2	S to L	SA to SH	150	50	high	Stylosanthes, Aeschynomene, etc.

Table 1 contd…

BNF Interventions	Social benefits (0, 1 to 5)					Land Use system	*Geo. range*	Pot. BNF	Current BNF	Pot. Impact	Specifics
	Income gen.	Food sec.	Land cons./rest	*C*	*Bio* D						
Dune stabilisation	0	0	5	5	3	Waste. Degraded Low N soils	A	120	60	High	Casuarina
Woodlots	3	0	5	4	2		SA to SH	150-300	50	High	Acacia spp
Afforestation	0	0	5	5	4		SA to SH		50		Numerous sp
Woody fallows	1	0	4	3	2	S to L	SH to H		50		P solubilisation
Herbaceous fallows	1	0	4	3	2	S to L	SH to H	200	50	Med	Mucuna, Pueraria, S. rostrata
Mixed woody/herbaceous	1	2	4	4	4	S to L	SH to H	300		Med	Numerous
Woody parkland	1	0	2	2	2	S to M	SA to SH	100	50	Med	[thorny] Acacia spp
Boundary trees	1	0	3	3	2	S to L	SH to H	60	30	High	Numerous

Land Use Systems: S=small land holdings; L=large holdings; W=wasteland.
Geo range: SA=semi-arid; SH=subhumid; H=humid; A=arid; MA=mid-altitude; HA=highland.

1.4 Strategic alliance to combat soil fertility degradation through holistic approach (CIAT-TSBF-ICRAF)

Soil fertility degradation has been described as one of the major constraints to food security in developing countries, particularly in Africa. Despite proposals for a diversity of solutions and the investment of time and resources by a wide range of institutions it continues to prove a substantially intransigent problem. The rural poor are often trapped in a vicious poverty cycle between land degradation, fuelled by the lack of relevant knowledge or appropriate technologies to generate adequate income and opportunities to overcome land degradation. Three international institutions, CIAT, TSBF and ICRAF, have joined together to form a strategic alliance, the goal of which is 'to improve rural livelihoods in Africa through sustainable integrated management of soil fertility' (Figure 1). The three partners have made significant contributions to combating soil fertility degradation over the past decade and have also a long record of collaboration through joint research projects. The alliance will go further however by building on existing networks and partnerships to implement a fully integrated programme of research and development activities. This triple alliance is regarded as the first step in a wider partnership consistent with the process of integration of international, and national, agricultural research activities.

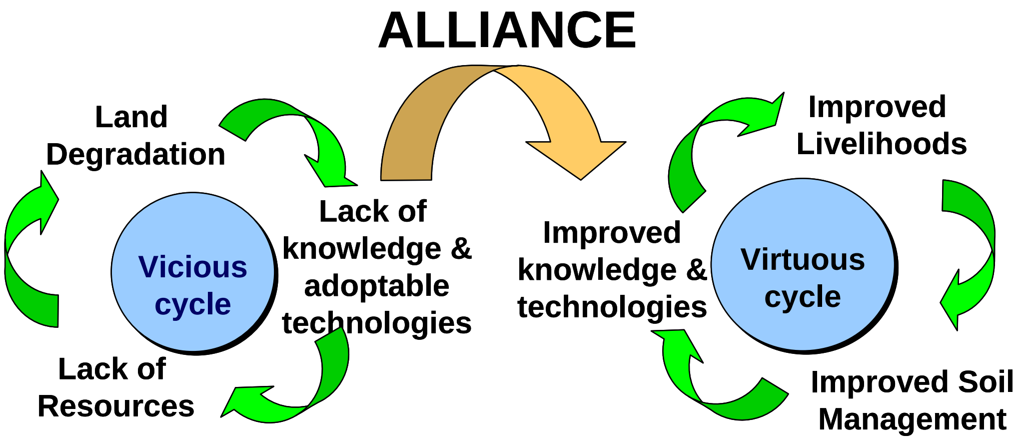

Figure 1: Combating soil fertility degradation: generating ISFM knowledge to improve rural livelihoods.

1.5 Ecoregional alliance (CIAT-IITA-ICRISAT-ICARDA) on legumes

The ecoregional alliance, formed in 2000 by CIAT, ICARDA, ICRISAT and IITA, reinforces the regional and global dimension of the evolving research and development paradigm. The alliance represent a unique concentration of multidisciplinary expertise in legume research, with over 65 qualified scientists working on various aspects of legume production and utilization (genetic resources and breeding, agronomy and microbiology, plant protection, quality and post-harvest processing, and socio-economics). This ecoregional alliance sees achieving synergy in legume research as a key opportunity to make progress in improving food security, combating environmental degradation and alleviating poverty in developing countries. A BNF-CP would be an important axis of collaboration among the ecoregional alliance centers for all of whom legumes are a high priority. The BNF-CP would not, however, be the only area of collaboration on legumes research among the four centers. The ecoregional alliance will continue to explore other avenues for collaboration on legume genomics, adaptation to biotic and abiotic constraints, agroecosystem health, and rural innovation.

1.6 Systemwide Program on Soil, Water and Nutrient Management (SWNM)

SWNM is a systemwide global program of CGIAR created in 1996 to help multiple stakeholders rise to the challenge to reverse degradation of soils through the development of sustainable practices for managing soil, water, and nutrients. Operating through four complementary research consortia (combating nutrient depletion, optimising soil water use, managing sloping lands for erosion control, and integrated soil management), the SWNM program has developed a series of decision support tools and methodologies that are being tested across the different regions in Africa, Asia and Latin America covered by the program. SWNM program could serve as an important vehicle to test, promote and deliver BNF-efficient legume technologies to improve rural livelihoods of farmers in the tropics.

1.7 Systemwide Program on Participatory Research and Gender Analysis (PRGA)

PRGA is a CGIAR systemwide program on participatory research and gender analysis for technology development and institutional innovation. The PRGA program develops and promotes methods and organizational approaches for gender-sensitive participatory research on plant breeding and on the management of crops and natural resources. PRGA is cosponsored by CIAT and three other CGIAR centers (ICARDA, CIMMYT and IRRI). A recent review carried out by the PRGA program found very little relevant experience in ISFM research with attention to gender-related needs or constraints (Kaaria and Ashby, 2001). This lack of a client-oriented, gender sensitive approach to the basic design of ISFM technologies has contributed not only to poor adoption but also to inequity. As a result the PRGA is currently supporting research to test novel approaches to pre-adaptive research for ISFM which are incorporating client-oriented participatory research methods, such as gender and stakeholder analysis, into very early stages of technology design. PRGA currently supports research on gender-differentiated approaches to developing technology for integrated nutrient management being conducted by CIAT's parricipatory research team. Linking BNF-CP with PRGA program could markedly enhance the ability to develop appropriate and adoptable legume technologies in the tropics. PRGA, together with ICRISAT, conducted a study on impact of participatory methods in the development and dissemination of legume soil fertility technologies and identified lessons that will be useful in BNF work (Snapp, 1998; 1999a, b; Snapp et al., 2001; Johnson et al., 2001). TSBF is a partner in implementation of a subsequent project on the use of participatory approaches in research on natural resource management to improve rural livelhoods for women farmers in risky environments.

2. BNF-related research accomplishments of CIAT-TSBF on grain legumes and multipurpose legumes

BNF research at CIAT started in the 1970s. Several scientists including Peter Graham, Judy Kipe-Nolt, Douglas Beck (Beans) and Dick Date, Jack Halliday, Rosemary Bradley, Richard Thomas (Tropical Pastures) and others made significant contributions to developing practical ways to enhance BNF in legumes. CIAT maintains a collection of *Rhizobium* strains of 5,628 strains.

2.1 Grain legumes

2.1.1 Genetic improvement of BNF efficiency in grain legumes: Common bean as a case study

BNF research in common bean (*Phaseolus vulgaris* L.) has spanned the range of strain selection, host improvement, and agronomic management, and recently QTL (quantitative trait loci) studies have been initiated (Graham, 1981; Graham and Temple, 1984; Kipe-Nolt and Giller, 1993; Kipe-Nolt et al., 1993). Thus, the case of bean illustrates both some of the successes and failures of BNF research. An important attribute of common bean, justifying its inclusion in low input systems, is the ability to fix atmospheric N and thereby reduce the depletion of soil resources. Beans in tropical environments are capable of fixing from 50 (CIAT, 1987) to 80 kg N ha^{-1} (Castellanos et al., 1996). Yet, actual N_2 fixation in bean cultivars is generally low when compared with many other grain legumes. Early research in the late 1970s indicated that this poor BNF is not due to an intrinsic inability of beans to nodulate because profuse nodulation can occur in controlled conditions in the greenhouse and in some soils. Although poor nodulation is frequently observed, soils in most bean growing areas contain large numbers of compatible and effective rhizobia. Selection of adapted *Rhizobium* strains for beans sown directly in pots of soils containing large populations of indigenous, compatible rhizobia has resulted in yield increases when these strains were tested in the field.

Graham and coworkers field tested more than 600 cultivars of common bean under short-day subtropical conditions and found greatest N_2 fixation in the indeterminate, climbing beans (Graham and Rosas, 1977; Graham, 1981; Graham and Temple, 1984). A very active program of breeding for improving BNF in beans (crossing and recurrent selection) in the early 1980s in small-seeded bush beans generated a number of advanced lines (designated as RIZ lines). Field evaluation of these RIZ lines in the late 1980s in Colombia indicated that the RIZ lines generally nodulated better and fixed more N_2 than their parents (Kipe-Nolt and Giller, 1993). However, when compared with other CIAT bred lines, RIZ lines were no better in N_2-fixation than some other bred lines that were not specifically bred for BNF potential, in particular BAT 477 (see below). A major lesson learned from this breeding effort was that the field sites used for breeding -- for better BNF -- in Colombia are rich in N supply thus the selection pressure was not adequate. These results are in contrast to field evaluation efforts of bean germplasm on infertile soils in Africa, which met remarkable success in identification of several genotypes with superior adaptation to low N supply (Wortmann et al., 1995). These genotypes improved grain yield on farmers' fields, at least in part due to superior BNF.

Research work done in the late 1970s and most of the 1980s indicated that environmental constraint(s) limit N_2 fixation in the field. Phosphorus deficiency -- which affects 60% of bean growing area -- was considered to be the main factor limiting N_2 fixation in the field. In the early 1990s specific research into P x BNF interactions in beans was conducted in close collaboration with INRA, France. Extensive effort has been dedicated to seeking sources of bean germplasm tolerant to low P with regard to BNF and to identifying the respective genes. The selection parameter used in breeding for greater BNF was total N accumulation. This work resulted in identification of cultivars and strains that fix N more efficiently in low P soils. Among them BAT 477 is an unusual bred line in several respects. It is one of the most widely adapted drought-tolerant lines found to date. It has demonstrated unusually high general combining ability among lines within race Mesoamerica. With regard to BNF potential, it has been shown to be one of the best N_2 fixing genotypes under unstressed conditions in different soil types as well as stressed conditions of both drought and low P. This suggests that the BNF genes of BAT 477 are especially stable, and therefore are of particular interest for intensive study, and for deployment in bean cultivars.

In the late 1990s, recombinant inbred lines (RILs) of BAT 477 x DOR 364 were used to identify QTLs for BNF under low P stress conditions in collaboration with INRA, France (Ribet et al., 1997; Valdez et al., 1999). Results obtained indicated that most QTL contributing to greater total N and/or dry weight (DW) proceeded from BAT 477 in the F5 generation, although one QTL that contributed to total N proceeded from DOR 364. It is no surprise that, for a trait as ubiquitous in *Phaseolus vulgaris* as is nitrogen fixation, some positive QTL are found where not expected. Yet, in its development, BAT 477 was never selected consciously for nitrogen fixation.

In the late 1980s to early 1990s, a collaborative program between CIAT and NARS to select bean rhizobia strains adapted to specific areas and cultivars has been successful in Cuba and Cajamarca, Peru. In Cuba it has been possible to reduce N applications on bean by 80% through inoculation, and a BNF "package" of strain, genotype and low levels of P inputs gave yields equal to the standard variety with high inputs. The most productive strains are now produced commercially and used by farmers in these two countries. In the majority of cases, however, successful inoculation response trials in Latin America and Africa have been sporadic at best. But in Central America a regional collaborative project tested the benefits of inoculation with selected strains and found an average of 14% yield increase over 39 trials. CIAT maintains rhizobia strain collection and database. In the early 1990s research on *Rhizobium* focussed on two activities: 1) evaluation of strain N_2 fixation effectiveness and strain x cultivar interactions; and 2) evaluation of factors affecting rhizobial competitiveness. The latter was approached through development of strains genetically transformed to express glucuronidase in nodules, enabling easy wide scale analysis of inoculation events. This work was aimed to identify strains capable of high levels of N_2 fixation across a broad range of cultivars and a high degree of competitiveness under prevailing environmental constraints. CIAT has developed a group of 20 strains transformed with the *gus* gene while maintaining the symbiotic and competitive characteristics of the wild type. These genetically modified strains could serve as valuable tools to evaluate competition x environment interactions.

Another valuable tool that was developed in 1990s was a series of non-nodulating lines. Mutagenesis was employed to create a mutant with a total lack of nodules. The non-nodulating gene in turn was backcrossed into a series of elite lines, to have at hand a ready tool for estimating the amount of nitrogen fixation in any given situation, by comparing non-nodulating and wild type paired lines.

2.1.2 Lessons learned: In summary, lessons with nitrogen fixation in bean can be summarized as follows. BNF has not been a panacea, neither on the side of strain selection nor breeding of the host, but modest progress has been registered. On the one hand, even if response to inoculation is not dramatic, the technology is so inexpensive that any response at all is economically viable. On the other hand, the environment is at least as limiting on BNF as is the strain and the host. Therefore the benefits of BNF are best expressed in the context of an agronomic management system that addresses other components of the crop, especially phosphorus, drought and not infrequently starter N. Selection for BNF capacity under physiological stress has revealed genotypes (and possibly genetic systems) that are worth exploiting more fully and which could hold keys to broader progress.

2.2 Tropical forage legumes

2.2.1 Selection of rhizobial strains and development of BNF technologies for forage legumes

BNF research on tropical forage legumes initiated in the late 1970s and continued throughout the 1980s and 1990s (Date and Halliday, 1979; Sylvester-Bradley et al., 1983, 1988, 1991; Sylvester-Bradley, 1984; Thomas, 1993, 1995; Thomas et al., 1997). Taking into account the wide range of forage legume genera being evaluated, about which very little information concerning BNF was available, the main priority was initially to determine need to inoculate. After improving the methodology for evaluation of need to inoculate, specifically by ensuring that the presence of mineral N was not interfering with the evaluations, by using different methods to immobilize mineral N, it was found that a surprisingly large proportion of the legumes showed responses to added N. This indicated that the naturally occurring rhizobial populations were inadequate, either numerically or in nitrogen fixing capacity under the given soil conditions. A program was developed whereby rhizobium strains which a) were able to compete with the native rhizobial population and b) would be effective on as wide a range of legume species as possible, were selected. A new method for strain selection, viz. the screening of large numbers of strains in undisturbed soil cores, was developed, and proved to be highly successful. Many statistically significant responses to rhizobial inoculation in the field were obtained.

With funding from the UNDP, a network of scientists was established in the mid 1980s to evaluate legume-rhizobium symbioses in 14 countries of Latin America. The findings of this network were brought together at a workshop held at CIAT in 1987 where appropriate strain recommendations were made, and continue to be revised as a result of field evaluation by network members. The proceedings of this workshop were published in 3 volumes entitled “The legume-rhizobium symbiosis, proceedings of a workshop on evaluation, selection and agronomic management”. A list of recommended *Rhizobium* strains for herbaceous and shrubby legumes is available. In addition, a manual of methods for legume-rhizobium studies plus an accompanying audio-visual package has been available for interested researchers in national programs.

The marked responses to rhizobial incoulation observed in these trials led to the realization that a new way of inoculating the seeds of legumes was needed, so that the technology would be more available to farmers. In view of the fact that vaccines for both humans and animals are vital in tropical countries, and that the infrastructure for making them available is being developed in many areas, it was considered that this technology might also be useable for rhizobial strains. Traditional peat-based inocula need a large refrigerated storage space, and even if stored under refrigeration have a shelf life of only 6 months. Several different strains of rhizobia are needed for the different legume species being selected for pasture-based production systems, which complicates even further the possibility of supplying good quality traditional peat-based inoculants to farmers. CIAT therefore initiated a project to develop freeze-dried rhizobial inocula, also with funding from the UNDP. This project demonstrated that such inocula could survive for several years in vacuum-sealed vials, and that they can be suspended in water and applied to the seeds with high survival rates. This technology could well be a realistic alternative for supplying forage legume seeds and rhizobial inocula to farmers.

Work on quantification of N_2 fixation using ^{15}N dilution studies was carried out in the late 1980s through a Swiss Development Corporation funded project (Cadisch et al., 1989, 1993). This project demonstrated the need to maintain adequate levels of both P and K for legume-based pastures that rely on biologically fixed N to supply the N requirement of the pasture.

CIAT researchers were also the first to demonstrate fungal/bacterial inhibitory role of *Bradyrhizobium* strains isolated from tropical forage legumes (Kelemu et al., 1995). Screening of 15 strains of *Bradyrhizobium* from CIAT collection with *in vitro* tests showed that *Bradyrhizobium* can inhibit mycelial growth, reduce or prevent sclerotial formation, and inhibit sclerotial germination in *Rhizoctonia solani*. In addition, cell-free culture filtrates of three strains of *Bradyrhizobium* had inhibitory effects on the growth of the bacteria *Escherichia coli* and *Xanthomonas compestris*. The antifungal/antibacterial property may increase the competitiveness of *Bradyrhizobium* strains and enhance the chance of nodule occupancy and other beneficial responses with compatible forage legumes. Further research is justified to determine the impact of *Bradyrhizobium* strains on integrated disease and pest management in crop-livestock systems.

2.2.2 Role of legume-BNF in crop-livestock systems (Latin America)

As the objective of selection for improved N_2 fixation was mostly achieved, research in 1990s broadened from N_2 fixation *per se* to the role of the legume and N in productive and sustainable pasture and crop-pasture systems (Thomas, 1992; 1995). This work showed that tropical forage legumes have the capacity to meet the requirements to balance the N cycle of grazed pastures. It also showed that the actual amounts required could depend on the rate of pasture utilization and the efficiency of recycling via litter, excreta and internal remobilisation. The efficiency of N_2 fixation (%of legume N derived from fixation) was found to be usually high in tropical pastures (> 80%) and is unlikely to be affected by inorganic soil N in the absence of N fertilizer application. This work resulted in a recommendation that an estimate of the amounts of N fixed by tropical forage legumes could be obtained from simple estimates of legume biomass provided tissue levels of P and K are adequate for plant growth.

In an on-going and long-term crop-pasture rotations experiment in tropical savannas of Colombia, N dynamics were studied under cereal monocultures and rotations with greenmanure legumes with the objective to determine the use efficiency and fate of N derived from inorganic and organic sources (Friesen et al., 1998). Results indicated that N recovery by crops from residues was low (7-14%) while recovery from fertilizer was far greater (26-50% in biomass). Sequential measurements of soil profile mineral-N concentrations indicated a large accumulation of nitrate content to 1-m depth through the dry season and substantial nitrate movement through the soil profile during the wet season under both rotations and monocultures. Thus in a high leaching environments of humid tropics, poor N supply-demand synchrony can result in substantial leaching of nitrate below the crop rooting zone and eventual contamination of the ground water. Use of deep-rooted crop, forage and fallow components could minimize N losses from legume-based systems in the tropics.

2.2.3 Lessons learned: It was realized that the main constraints to the widespread adoption of forage legumes include a lack of legume persistence, the presence of anti-quality factors such as tannins, variable *Bradyrhizobium* requirements and lack of acceptability by farmers. But “lack of legume persistence” is not really a limitation if the seed is cheap enough. The legume seed can be broadcast into an already established pasture. Seed can cost as little as $4/kg and only 3 kg of Stylosanthes are needed per hectare. The problem is that there is not enough work done on participatory evaluation of legumes with farmers. What is needed here is better collaboration among stakeholders to really get legume adoption under way in the tropics.

2.3. Organic resource database and organic matter management

In areas where access to adequate quantities of mineral fertilizers is beyond the reach of low resource endowed farmers, organic sources of nutrients of animal and plant origins e.g. legumes will continue to be a critical source of nutrients (Palm et al., 1997). Organic materials influence nutrient availability (i) by nutrients added, (ii) through mineralization-immobilization patterns, (iii) as an energy source for microbial activities, (iv) as precursors to soil organic matter, and (v) by reducing the P sorption of the soil. The TSBF-SWNM (CNDC) organic resource database (ORD) with over 2000 data entries has been used to construct a decision support system (DSS) for organic matter management based on contents of nitrogen, polyphenol and lignin. Most studies indicated a linear response between N content and fertilizer equivalency values (FEQ) of the material with an increase of 8% FEQ for every increase of 0.1% N. In a recent study on evaluating FEQ of *Tithonia diversifolia*, *Tephrosia, Sesbania* and pigeon pea, yield increases up to 48% were recorded. This decision tree provides farmers with guidelines for appropriate use of organic materials for soil fertility improvement. On-going TSBF network experiments are now addressing the organic/inorganic nutrient interactions to allow the refinement of the recommendations to farmers. A systematic framework for investigating the combined use of organic and inorganic nutrient sources includes farm surveys, characterization of quality of organic materials, assessment of the FEQ value based on the quality of organics, and experimental designs for determining optimal combinations of nutrient sources. The desired outcome is tools that can be used by researchers, extensionists and farmers for assessing options of using scarce resource for maintaining soil fertility and improving crop yields (Palm et al., 1997). With the recent success of CIAT scientists with their partners in linking of the DSSAT crop models with the CENTURY soil organic matter model (Gijsman et al., 2002), the nutritive value of organic substrates for crop production can be analyzed under a range of climatic and soil conditions and for many different crops. The combined DSSAT-CENTURY also proved to be an excellent tool for evaluating the SOM pattern under low-input systems.

A combination of resource flow mapping, ORD and FEQ has helped farmers to identify options for enhancing farm productivity and sustainability. Analysis of organic resource data indicated a hierarchical set of critical values of nitrogen, lignin and polyphenol content for predicting the "fertilizer equivalence" of organic inputs. TSBF and CIAT with a wide range of partners are also developing methods for disseminating ISFM options through processes of interactive learning and evaluation among farmers, extensionists and researchers.

2.4 Legumes in smallholder systems in Africa: Lessons learnt from experiences of other institutes and initiatives

The potential for legumes is increasing for many smallholder farming systems in Africa as soil fertility declines and livestock management is intensified (Wortman and Kirungu, 2000). These two researchers summerized lessons from several cases where legumes have been promoted for soil improvement or forage. The cases included Mucuna in Benin, Sesbania and Tephrosia in Zambia, Calliandra in Kenya, improved fallows and green manures in Rwanda, Stylosanthes in west Africa, Tephrosia in eastern Uganda, best-bet niche options in central and eastern Uganda, and Lablab in western Kenya. These cases included those where the practice was well adopted by farmers, as well as cases of unconfirmed promise, and adoption failure.

Over 15 years of work in West Africa with leguminous trees in alley cropping systems and *Mucuna* cover crops has led to a series of conclusions. First of all, such systems are technically sound and do maintain crop yields at substantially higher levels than traditional cropping systems. However, their adoption by farmers is relatively low or absent because (i) the appropriate niches for such systems were not properly identified (e.g., alley cropping must be targeted to high population density areas where firewood is needed and fertilizer is not easily available) and (ii) resource poor farmers require immediate benefits besides improved soil fertility.

As a result of above developments and maybe due to the existence of crop improvement and resource management programs in the same institute, dual purpose grain and fodder legumes have been developed at IITA which improve the soil fertility status besides providing grains and fodder. Such legumes usually have a large proportion of N derived from the atmosphere, a low N harvest index and produce a substantial amount of above ground biomass. Residual effects on a cereal crop are often dramatic and fertilizer use to a subsequent cereal can be cut by 50% while still producing similar maize yields as a fully fertilized maize crop. Furthermore it was found that, e.g., soybean and cowpea could be false hosts for *Striga hermonthica*. One dual purpose soybean variety, TGX-1448-2E was specifically appreciated by farmers in Northern Nigeria, who commented that this variety yields more, produces more biomass than their own varieties. In addition, their succeeding maize/sorghum crops gave good yields with less N fertiliser than they would normally apply. The highest net benefits for the two seasons (1450 US$) were obtained with the rotation of TGX 1448-2E followed by the local variety Samsoy 2 (1000 US$). The lowest net benefits (600 US$) were obtained with *lablab* (Sanginga et al. 2001).

3. Need for a multidisciplinary systems approach to implement an Integrated Soil Fertility Management (ISFM) agenda in the tropics

From our past achievements, it is clear that BNF can contribute directly to the needs of a growing crop or can be added to the soil so contributing to its fertility. For sustainable agriculture in the tropics, there are two options: inorganic N fertilizers and BNF technologies that are less dependent on external purchased inputs. Approaches relying purely on external inputs are not often feasible, particularly for resource-poor farmers of the smallholder systems. In Africa, where the price of inorganic fertilizers is several times higher than world price, alternatives to inorganic fertilizers are especially important. A consensus has emerged that systems of ISFM are the only way forward, and it is in this context that we must consider the inputs from BNF (Figure 2).

Decision by farmers to adopt ISFM is influenced by (and influences) a range of factors which can be grouped in 4 main dimensions, biophysical, economical, social, and policy (Kaaria and Ashby, 2001). The biophysical dimension influence on farmers include the basic characteristics of the BNF technologies as well as the overall quality of the resource base. The main economic factor that influences whether farmers practice ISFM is whether the economic benefits outweigh the costs, especially in the short run. ISFM/BNF technologies are often labor intensive and if labor costs are too high—or come at the wrong time of the year when farmers are busy with other activities-- then farmers can not profitably adopt the technologies. Often labor-intensive practices like ISFM are only profitable when used with high value commercial crops. Social dimension also influence adoption and impact of ISFM. Where crop production responsibilities (and rights) are gender specific, ISFM technologies need to be consistent with these, e.g., appropriate for women work schedules or don't add additional labor for women when men get the benefits. Legumes can have important human health benefits, although care must be taken to assure that foods are properly prepared (e.g., mucuna) and culturally appropriate (if people won't eat them then may be can use as animal feed). Finally, a supportive policy environment is key to achieving widespread adoption. Fertilizer prices should be rational (not subsidized or taxed) and reflect real costs. This is the best way to ensure that farmers use the right combinations of organic and inorganic soil fertility management practices in their technologies. In addition, property tenure security is important to realize benefits of long-term investments, land ownership or long-term rental/use arrangements are important. Infrastructure investments such as roads and communications that open up marketing opportunities can help make adoption of ISFM profitable.

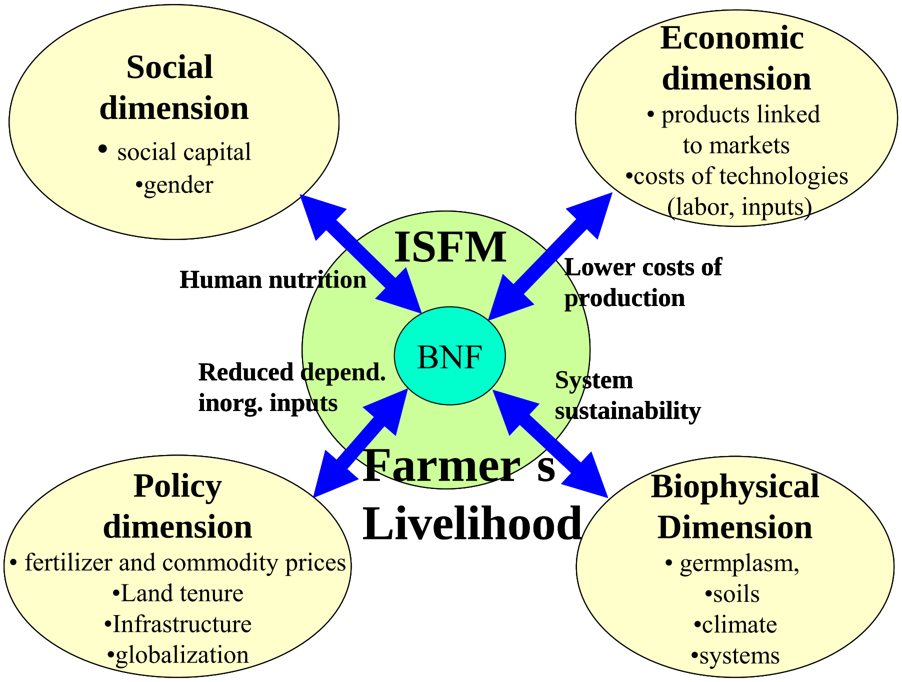

Figure 2. The key role of legume-BNF in the overall integrated soil fertility management (ISFM) strategy.

Legume BNF can be a key input to ISFM. When legume BNF technologies are appropriately designed taking into consideration the incentives provided by each of these four dimensions, they could have positive impacts in each dimension as well. Legume-BNF technolologies can improve the sustainability of crop-livestock systems (biophysical), improve profitability, contribute to improved nutrition and gender equity (social). At the marco level, increased use of legume-BNF technologies could reduce use of costly imported inorganic fertilizers (policy).

Most tropical soils have low inherent fertility and exhibit a variety of edaphic and climatic constraints including water stress, nutrient deficiency, low organic matter, and high erodibility. Inadequate soil and crop management has exacerbated these problems to an alarming extent. As a result of insufficient levels of nutrient replacement for that taken in harvest and other losses, high negative nutrient balances are commonly reported, particularly in sub-Saharan Africa.

Intensification of agricultural production on smallholdings is required to meet the food and income needs of the poor, and this cannot occur without investment in soil fertility. Investing in soil fertility management is necessary to help households mitigate many of the characteristics of poverty, for example by improving the quantity and quality of food, income, and resilience of soil productive capacity. The effects of soil fertility degradation are not confined to the impact on agricultural production. The living system of the soil also provides a range of ecosystem services that are essential to the well-being of farmers and society as a whole.

BNF-related research should proceed along the process-component-systems continuum and lead to demand-driven, on-farm problem-solving. Given the diversity of N_2-fixing organisms, symbioses and habitats in which these organisms operate and the wide application and demand for fixed-nitrogen, BNF studies are by definition multi-disciplinary. Under the first paradigm for BNF research, microbiologists, plant physiologists and agronomists recognized the need for collaboration to respond to challenges posed by better management of nitrogen fixation, and now is the time to recognize the additional strengths derived from expanding this collaboration into wider interdisciplinarity as a means of better translating research findings into social benefits. Systems approach includes the involvement of stakeholders to fine-tune problem definition, the research itself, and the implementation of results. Stakeholders are farmers and citizens on farm and community levels, and policy makers and planners at higher level of aggregation. A comprehensive systems approach could be a necessary condition for the development of innovative, BNF-efficient, legume-based sustainable systems of the future. A programme of work must build on and use methods that have already proved successful and also develop and borrow others where significant gaps in understanding or application occur.

4. ISFM challenges in relation to BNF-CP

The implementation of ISFM strategies on farms is likely to make the biggest contribution to agricultural sustainability in the tropics during the coming decade. When combined with robust, highly productive crop varieties, it is not uncommon for such systems to double yields in farmers' fields. The use of improved varieties is an integral part of the ISFM approach; ISFM is a specific strategy under the overall INRM research framework that aims at lifting the borders between crop improvement and natural resource management. A vital aspect of these strategies is the incorporation of farmers’ indigenous knowledge at an early stage of systems development to enhance the adoption of ensuing technology.

Considerable evidence exists that farmers have accumulated knowledge relevant for agronomic management (Carter and Murwira, 1995; Murage et al., 2000). Encouraging as this is, increasing land degradation, including often substantial soil fertility decline, suggests that locally devised methods, on their own, are no longer effective enough to cope with rapidly changing pressures on farmers (Johannes and Lewis, 1993; Pinstrup-Andersen and Pandya-Lorch, 1994; Murdoch and Clark, 1994).

Farmers generally possess a vast body of knowledge about environmental resources in their farms but this knowledge is largely based on observable features (Talawar and Rhoades, 1998) rather than generalized knowledge. There is a general lack of process-based knowledge about agro-ecosystem function which is needed to cope with change, especially since much of it is unprecedented (i.e. climate change). This is in particular true for colonist farmers (Muchagata and Brown, 2000). In essence, lack of knowledge creates uncertainty that obstructs sound decision-making under conditions of change. This uncertainty about agro-ecosystem function prevents farmers from taking decisions that are too risky, and may have contributed to their reputation of being risk-averse. However, recent research points out that scientific knowledge can reduce farmers' decision-making uncertainty by enhancing local knowledge (Fujisaka, 1996). Some examples already exist that show how this can have positive synergistic effects for agro-ecosystem management (Steiner, 1998; Norton et al., 1998; Robertson et al., 2000).

4.1 Research needs

A holistic systems approach of ISFM is needed to address the smallholder to medium scale farming sector throughout the diverse agroecological zones of the tropics. This systems approach does not exclude process and molecular studies, but rather suggests that these tools be focused upon recognized constraints within farming systems. Research efforts on legume-BNF related aspects thereby become tools toward larger purpose, particularly in achieving food security and improving the diets of poor people in the tropics.

4.1.1. Evaluating genetic diversity to overcome environmental constraints

Environmental factors affect BNF via growth and development of the host plant, the bacteria and also the process of interaction between the symbionts from the time of infection through the development of the nodules to the production and transport of products. The identification of the processes that are most sensitive to environmental constraints promises the greatest success in breeding programs or in an improvement of agronomic practices (Rao, 2001). The major environmental factors affecting BNF in the tropics are drought, soil acidity, soil nutrient deficiency and soil salinity. As substantial genetic variability in tolerance to most environmental constraints exists in both host legumes and rhizobial strains (Hungria and Vargas, 2000), there is potential for breeding and selection for improved genetic adaptation.

Significant gains in impact can be achieved in the short to medium term by taking advantage of the huge legume and *Rhizobium* gene banks in participatory field evaluation and identification of stress-adapted legumes to specific ecological niches.

Drought: It was recognized that drought affects BNF in legumes significantly. Decrease in soil moisture causes a rapid decline in the numbers of rhozobia in soil. However, *Bradyrhizobium* strains are more tolerant of desiccation than strains of *Rhizobium* over short periods (Bushby and Marshall, 1977). Rates of N_2-fixation by legumes are more sensitive to reductions in soil moisture content than other processes such as photosynthesis, transpiration, leaf growth rates or nitrate assimilation (Serraj et al., 1999). Ureide-exporting legumes with determinate nodules appear to be more sensitive to drought than amide-exporting legumes (Serraj et al., 1999).

Given the expansion of drought at an alarming state, especially in sub-Saharan Africa, and the need for incorporation of legumes into systems to improve soil fertility, there is a real need to improve the drought resistance of nitrogen fixing legumes. Although challenging, there is an opportunity to improve drought resistance using the existing genetic diversity and available tools in genetic engineering. CIAT has been working on development of drought resistant bean varieties, and identified resistant materials like BAT 477, to be used as genetic sources. A drought protocol was also recently developed for improvement of the genetic adaptation of beans in Africa (Amede et al., 2002). A possible strategy in the short-term could be improving water-holding capacity of tropical soils by increasing soil organic matter content and rate of water infiltration while reducing run-off and soil erosion. As most grain legumes in the tropics are grown as intercrops or relay crops, selecting best companion crops and adjusting the planting dates could minimize water stress effects on BNF.

Soil acidity: Soil acidity is expanding in the humid and sub-humid tropics, mainly caused by improper land use and high rainfall intensity that encourage leaching of cations. Effects of soil acidity and the associated Al (aluminum) toxicity and P deficiency on BNF could be minimized through increasing the rhizosphere pH. One immediate option is liming but this is beyond the reach of resource-poor farmers, particularly in Africa. There is a consensus that continuous cultivation of legumes over longer time could lead to soil acidification. Therefore, crop rotation or intercropping legumes with cereals (maize-bean or sorghum-cow pea) is one sustainable strategy to improve BNF. Moreover, there are some tropical legumes that produce root exudates (mucilages & organic acids) that could minimize the effects of soil acidification through complexing Al ions. Other potential strategy is to identify legumes less sensitive to Al toxicity. Bean researchers at CIAT are breeding for improved Al resistance. ECABREN bean network in Africa has identified bean materials that are less sensitive to Al toxicity when grown under acidic soils of Democratic Republic of Congo. CIAT researchers in collaboration with NARS partners have selected a number of tropical forage legumes with very high adaptation to acid soils of the tropics (Rao, 2001).

Soil nutrient deficiency: As mentioned earlier, the most limiting nutrient for BNF is known to be P, which becomes limiting in most tropical soils not only for legumes but also for all other crops. The P deficit in soils of the tropics is the result of combined effect of low inherent P content, very high P fixation, and limited application of soluble P (Rao et al., 1999). Some legumes (e.g. pigeonpea, chickpea) are much more efficient in utilizing P in P-fixing soils, mainly through release of organic acids that increase its availability. Moreover, ECABREN of CIAT identified bean materials that are performing well under low N, low P and low pH soils of Eastern & Central Africa, indicating genetic difference in nutrient use efficiency. Other institutes are working with P efficient cowpea and soybean (Sanginga et al., 2001).

Soil salinity: Legumes that are grown in the drought-prone environments of sub-Saharan Africa, with saline or sodic soils, are commonly exposed to salt stress. Soil salinity could affect BNF through induction of water stress, pH effect, direct effect of Na ions or a combined effect. However, the rhizobia were found to be more tolerant than the host plant. Since the initial effect of slat stress is commonly expressed as water stress, improving the soil water availability would improve salt resistance of both grain and multipurpose legumes. Another strategy is integration of well-adapted N-fixing perennial legumes to reduce soil pH through acidification.

4.1.2 Breeding/selection for improved BNF efficiency using conventional and molecular approaches

As indicated before (section 2.1) one of the bred lines of beans, BAT 477, is not only BNF-efficient but also well-adapted to major abiotic stress factors such as water stress and low P availability in soil. What is the probability that independent genes control tolerance of BNF to different stresses; that still other genes control BNF in stress-free environments; and these have come together in one genotype without any conscious selection? This is unlikely. Rather, the same genes probably confer high BNF under all these conditions. In this case, what mechanism could explain the tolerance of these genes to at least two stress factors? The genes of BAT 477 may be regulatory genes that are less sensitive to an internal stimulus that results in down-regulation and are thus less active in regulating BNF. Thus they confer high BNF under a wide range of conditions. It is significant that some QTL, which were tagged in BAT 477 under low P stress, also contributed to better BNF in the high P supply, suggesting that the corresponding alleles in DOR 364 (less adapted to low P supply) may not be expressed fully, even in optimal environments. Could gene regulation therefore limit BNF under optimal conditions? This hypothesis represents a different perspective on what restricts BNF in common bean. There is a need to investigate to what extent the poor BNF of common bean in fact reflects internal limitations of gene regulation.

4.1.3. Identification of niches within cropping systems

Legumes do occupy space and time in cropping systems and consequently, suitable temporal and spatial niches need to be identified within farming systems for widespread adoption by the farmer community. Temporal niches are defined by sequential or simultaneous occurrence of legumes while spatial niches are defined by the optimum location to plant legumes, based on farmers' production objectives. The latter often include under-utilized spaces on farm such as field boundaries, contour strips, or degraded fields. Snapp et al. (1998) identified six temporal niches for legumes. Spatial niches are also related to the existence of within-farm soil fertility gradients, created by inherent soil properties but more often by deliberate land management by the farmer. Such gradients are very often linked to farmers' wealth, and the overall socio-economic environment (e.g., access to input and output markets, credit schemes for intputs, etc.).

4.1.4. Proper legume management

Even nutrient use efficient and promiscuous legume germplasm requires proper crop management for optimal contributions of BNF. To alleviate P constraints to BNF, the simplest option is to apply soluble P fertilizer. In absence of such resource, another possible strategy is through application of rock phosphate. Preliminary evidence shows that certain legumes can immediately access P from unreactive rock phosphates where cereals do not have that ability (Vanlauwe et al., 2000a). Proper targeting of P in legume-cereal rotations has also been shown to significantly enhance the growth of maize after application of rock phosphate to herbaceous legumes (Vanlauwe et al., 2000b). A last alternative to alleviate P stress would be through application of farmyard manure which often contains considerable amounts of available P.

Even for N, except for the most efficient N_2 fixing legumes, there is often a need to supply a starter N especially for those legumes growing in low fertility soils. In multiple cropping systems of the tropics, it is possibly only the homestead, the most fertile corner of the farm that may not require external P inputs and/or starter N because of continual application of farmyard manure and household residues.

4.1.5. Approporiate INM strategies

The efficient use of fixed N incorporated in the legume biomass is the net result of the dynamics of N in the system and is affected both by intrinsic characteristics of N sources (legume residues, N fertilizers) and N sinks (crop uptake, soil N pools), and by environmental factors (temperature, soil moisture, rainfall intensity and distribution, etc.) that govern process rates. The decomposition and N release rates of crop residues and green manures depend on their composition (ratio of C:N and content of lignin and polyphenols as well as soil temperature and moisture and the interaction of residues with soil (affected by management) (Palm et al., 2001). N derived from organic sources which is not taken up by the crops or incorporated in the soil organic matter pool may be lost from the system through volatilisation, denitrification, and leaching. Improving synchrony of crop demand with the rate of legume residue decomposition is therefore of fundamental importance for the efficient use of N from leguminous green manures, covers and residues.

Within the INM framework, it is now recognized that both organic and mineral inputs are necessary to enhance crop yields without deteriorating the soil resource base. This recognition has a practical dimension because either of the two inputs are hardly ever available in sufficient quantities to the small scale farmer, but it also has an important resource management dimension as there is potential for added benefits created by positive interactions between both inputs when applied in combination. Such interactions can lead to improved use efficiency of the nutrients applied in organic or mineral form or both (Vanlauwe et al., 2001). Two sets of hypotheses can be formulated, based on whether interactions between fertilizer and OM are direct or indirect. For N fertilizer, the *Direct Hypothesis* may be 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*. Obviously, residue quality aspects will strongly determine the validity of this hypothesis. The *Indirect Hypothesis* may be formulated for a certain plant nutrient X supplied as fertilizer as: *Any organic matter-related improvement in soil conditions affecting plant growth (except the nutrient X) may lead to better plant growth and consequently enhanced efficiency of the applied nutrient X*.

Due to the complexity involved, the efficient use of participatory approaches in the early pre-adaptive stages of BNF research will ensure that BNF technologies are client-oriented and respond to the needs of farmers and other end-users. Farmer participatory research (FPR) is increasingly receiving considerable recognition in both international and national agricultural research and development organizations as an important strategic research issue, vital to achieving impacts that benefit poor people in marginal, diverse and complex environments. There is now a large body of literature that demonstrates considerable advantages and potentials of involving farmers in the research process. FPR can significantly improve the functional efficiency of formal research (better technologies, more widely adopted, more quickly and wide impacts), empower marginalized people and groups to strengthen their own decision making and research capacity to make effective demands on research and extension services and thus have payoffs both for farmers and for scientists.

4.1.6. Exploiting multiple benefits of legumes

Legumes very often provide other benefits besides fixed N to the cropping system of which they are part. Although rotational effects of legumes on subsequent cereals have often been translated into N fertilizer replacement values, rotational benefits can not always be explained in terms of N addition to the system. Besides improving the soil physical structure, deep-rooting perennial species may recover nutrients from the subsoil and reverse top-soil degradation (e.g., reverse soil acidification caused by fertilizer use, Vanlauwe et al., 2001). Legumes have also been shown to alter pest and disease spectra and to reduce the Striga seedbank. All the above processes are alleviating a constraint to crop growth and may consequently lead to improved use efficiency of applied N fertilizer, following the indirect hypothesis (section 4.1.5.)

4.2 Development needs

Innovations can be considered as demand-driven or as supply-driven. It is fair to say that in the eyes of farmers BNF options may belong to the second category, or at best, are a mixture of both. Furthermore soil fertility decline as an ISFM issue is complex, difficult to prevent given farmers' situation, and easily to detect only when yields drop sharply. This infers that many ISFM innovations will be most effective as conservative or preventative innovations; adopting means often to sacrifice short-term profits for reducing a decline in returns in the future. These innovations have often slow rates of adoption. Simultaneously, farmers vary in their risk preferences of an innovation, and perceptions are affected by information introducing further heterogeneity due different sources of and exposure to information. Often farmers do not face the problem targeted by the innovation or the innovation simply does not work. In addition, farmers will not commit to adoption of an innovation without successfully trialling it. If small-scale trials are not possible or not enlightening for some reason, as frequently the case in heterogeneous and fragile environments that are target regions for BNF, the chances of widespread adoption are greatly diminished. Conducting a trial incurs costs of time, energy, finance and land that could be used productively for other purposes. Furthermore the fact that economic and environmental conditions are rapidly changing today makes the adaptation of present land use systems and the process of including BNF in ISFM largely a process of managing the uncertain.

By taking a pro-poor approach, international agricultural research has developed the means to achieve large-scale impacts, responding to the demands of small-scale farmers for improved agricultural production and ecosystem services. Many ISFM options are locally profitable, even under intensely cultivated, land-scarce conditions. The knowledge-intensity and complexity of the ISFM approach, however, makes it difficult to translate local successes from one area to another, unless the factors favouring and constraining adoption are better understood. Increasing our understanding of where ISFM options are working, why, and for whom, will address the constraints limiting their wider use. The cost of not engaging in this research is likely to be enormous, in terms of greater poverty, stagnant and declining production, degraded ecosystem services, and the loss of intellectual property rights related to the local genetic resources of the soil.

Facilitating widespread use and impact of ISFM to solve soil fertility problems in the tropics will thus require a tighter linkage and feedback between strategic and adaptive research activities. The iterative process of learning and problem solving builds on indigenous knowledge, improves imperfect technologies, and empowers farmers and institutions. Addressing farmers' problems in a systems context generates management options better suited to their local needs. It also produces policy options that are suited to local institutional realities.

4.2.1 Involving stakeholders in the technology development process

The paradigm of involving farmers in research is based on strong evidence (Pretty and Hine 2001) that enhancing farmers technical skills and research capabilities, and involving them as decision-makers in the technology development process results in innovations that are more responsive to their priorities, needs and constraints. It is now widely recognized that these farmer participatory research (FPR) approaches may have wider applications for improving rural livelihoods in complex and diverse low potential areas where a "systems" approach is critical for the analysis and improvement of the production systems (Okali et al. 1994).

The active involvement of producers in the design of the ISFM system enables researchers and stakeholders to examine and understand the local farming systems and the larger context within which they exist, to incorporate local knowledge into technology innovation, and to develop locally appropriate solutions. A hallmark of FPR approaches is the link it establishes between the formal and local research systems (Ashby et al., 2000). This link enables farmers to express their technology needs and to help shape the technology developed through formal research. Participatory research decentralises control over the research agenda and permits much broader set of stakeholders to become involved in research, thereby addressing the differential needs of men and women for technical innovation.

Finally, farmer participatory experimentation and learning approaches represent an investment in the human and social capital available to poor farming families that can be harnessed to provide a systematic feedback process on farmers demands and priorities to research providers. These approaches build farmers' capacity to learn about knowledge intensive processes, biological and ecological complexities (Pretty and Hine, 2001) and can create a sustained, collective capacity for innovation focused on improving livelihoods and the management of natural resources.

4.2.2 Identification of uncertainty within a cropping systems approach

Scientific and local knowledge can be analyzed in relation to prevailing uncertainties about the innovation using an approach to uncertainty suggested by Rowe (1994). Rowe explains how uncertainty extends through many parts of the decision problem by distinguishing temporal, metrical, structural and translational uncertainty. Temporal uncertainty is associated with fluctuations of processes over time. Metrical uncertainty is introduced by errors associated with the estimation of parameters in a spatially varying resource base. Structural uncertainty is related to the imperfection of the decision model itself. Translational uncertainty arises from contrasts between the perspectives of individuals involved in the decision process.

For example: In deciding how to apply fertilizer, metrical uncertainty could be reduced by more precise definition of the relationship between inputs and response. Unlike farmers in highly intensive cropping systems, small-scale farmers in tropical systems do not have ready access to modern monitoring techniques. But they do possess long time series understanding of relations at on one location that has been generated through repeated observations. These accumulated observations can be related to relevant scientific soil parameters presented above, or their local counterparts, providing opportunities for the development of spatially explicit indicators.

Temporal uncertainty could be reduced by specifying the phase of crop development for which such a relationship is valid. Farmers have already assembled plenty of experience doing this when deciding, for example, when to enter a fallowed plot into the productive system. Scientists can help to render farmers' experiences made in traditional systems transferable to new cropping circumstances by relating them to underlying processes. On this basis, for example, indicator plants can specifically be selected and grown in new cropping systems. Simple monitoring devices such as leaf colour meters provide more opportunities.

Structural uncertainty could be reduced by defining more of the interactions of fertilizer applications with other variables, such as pest and weed infestation or rainfall, and translational uncertainty could be reduced by formulating the actions suggested to reduce the other types of uncertainty in terms which are relevant to the hillside farmers. Reducing structural and translational uncertainty is probably least amenable to formal scientific investigation. Structural uncertainty because of huge complexity of the interactions and the variation in the natural resource base in hillside environments, and translational uncertainty because of the little attention given by scientists to what matters for farmers. To reduce the former, scientists need to understand whether variation matters to farmers, and if so how much of it farmers are willing and able to manage. Relevant and informative trials are essential.

4.2.3 Identification of niches within a cropping systems approach

If farmers had complete information innovations identified as being relevant would be implemented without delay. Information about complex farming systems and their externalities is however not complete. A pragmatic choice of whether or not to implement an innovation at farm level has to be made about whether or not it is sensible to manage variation more closely, which is based on the interrelated questions of whether as-yet unmanaged variation is significant, whether it is controllable and predictable? All three conditions of significance, control and predictability must be satisfied before improvement can occur.

Significance: this is largely a question to be decided by individual farmers. But research has demonstrated that farmers are well aware of problems, and their natural tendency to experiment demonstrates their willingness to change.

Control and prediction: in most farms there is uncontrolled variation that is usually of no benefit to farmers. Farmers have the capacity for field-by-field control, and some in-field control. However the capacity to control is limited by farmers' experiences based on long-term observations that usually do relate to traditional cropping systems and control by these means cannot directly be used for new innovations. Second, for control to be effective, the relationship between variation of the controllable inputs and output must also be known to some degree.

The key to reducing uncertainty is on-farm trialling, preferably on the farmer's own property. For these reasons, rapid adoption of ISFM management options, involving combinations of unfamiliar and complex innovations that are difficult to trial, are unlikely to occur until they are considered relevant and essential by farmers. Furthermore, even if they are considered relevant and essential, appropriate designs of trialling have to be defined that overcome obstacles including:

- Treatments often must be implemented in combinations which make it difficult to determine from field observations alone the individual impacts of each element of the combination. For a trial to be worthwhile, the results of the trial must be observable.
- The effectiveness of some innovations may be very sensitive to temporal changes (e.g. weather conditions) or the quality of implementation. As a result trials give highly variable results from time to time.
- Economic comparisons based on typical agronomic small-scale research trials can be very misleading. However, the larger the trial is, the less likely the farmer is to make the investment in trialling.

4.2.4 Improving adoption and impacts of ISFM approaches

Principles of ISFM could influence diverse stakeholders in the tropics to alter the ways they address soils and their management, at a variety of scales. Promotion of ISFM approaches will require increasing participation of national and international research and development organizations, networks, NGO's, and extension agencies working in the tropics. Significant adoption of a range of ISFM technologies has been documented across a number of countries in sub-Saharan Africa. These include (a) integrated nutrient management, (b) micro-dose use of fertilisers, (c) improved manure management practices, (d) inter-cropping systems, (e) integration of multipurpose legumes, (f) improved fallows, and (g) biomass transfer of high quality organic inputs. However, much of these adoption studies have focused on conventional factors influencing adoption of agricultural technologies. The complexity of ISFM technologies and processes require the identification farmers' decision-making processes, constraints and opportunities for the adoption of ISFM technologies, and the identification of farmers' criteria for acceptability of BNF technologies. This will require improving understanding of the complex linkages between livelihood assets and strategies and ISFM adoption, and the impacts of ISFM technologies on rural livelihoods. Measuring the impacts of ISFM is a complex task. We need to develop innovative methods that enable to track changes in the systems through the use of participatory monitoring and evaluation systems to learn from successes and failures.

4.2.5 Building capacity at different scales

The capacity for ISFM research in the tropics is insufficient both in terms of the numbers of professional personnel and the essential laboratory facilities. ISFM is a knowledge intensive approach to soil management. Professional staff and students alike suffer from isolation and lack of access to up-to-date educational opportunities. Networks run by SROs and CGIAR Centres, such as the TSBF African Network for Soil Biology and Fertility (AfNet) and MIS (Integrated Management of Soils) consortium in Central America provide a vehicle of opportunity to correct this situation. A substantial number of short term, degree-related, and on-the-job training activities, across the tropics could help spread ISFM approaches at all national levels, including university curricula.

Some of the groundwork for scaling up and out has been laid through an emphasis on the synthesis of results and dissemination of information on the technologies and on developing partnerships between research, extension services and NGOs. TSBF-CIAT researchers have experience in developing and applying decision guides to assist extension staff and farmers in selecting among soil fertility options for different situations (Palm et al., 2001). The use of accessible, user-friendly GIS tools and geo-spatial datasets for the region can be used in the scaling process, by identifying recommendation areas for BNF technologies.

Scaling up requires sustained capacity building to build the requisite skills among the NARS to ensure that the work is involving and reaching the intended beneficiaries. It also requires building local capacities and empowering rural communities to improve their technical skills and decision-making on soil fertility, in support of scaling up and sustaining impacts of ISFM technologies. Efforts to engage with policy makers and private sector input suppliers and dealers should also be strengthened.

5. Summary and Conclusions

In this brief position paper we have argued that BNF is a key input to ISFM strategy to combat soil fertility degradation and for sustainable intensified agriculture in the tropics. The reasons for lack of success in solving the soil fertility problem lie substantially in the failure to deal with the issue in a sufficiently holistic way. Soil fertility decline is not a simple problem. In ecological parlance it is a 'slow variable', which interacts pervasively over time with a wide range of other biological and socio-economic constraints to sustainable agroecosystem management. It is not just a problem of nutrient deficiency but also of inappropriate germplasm and cropping system design, of interactions with pests and diseases, of the linkage between poverty and land degradation, of often perverse national and global policies with respect to incentives, and of institutional failures. Tackling soil fertility issues thus requires a long-term perspective and holistic multidisciplinary systems approach of integrated soil fertility management.

Developing adoptable legume-BNF technologies to combat soil fertility degradation remains to be a major challenge. Research and development efforts are needed to integrate BNF efficient and stress adapted grain and multipurpose legume germplasm into production systems to intensify food and feed systems of the tropics. Several key interventions are needed to achieve greater impact of legume-BNF technologies to improve livelihoods of rural poor. These include (a) integration of stress-adapted and BNF efficient legume cultivars in rotational and mixed cropping systems, (b) strategic application of inorganic fertilizers and organic residues to facilitate efficient nutrient cycling and appropriate replenishment of soil organic matter, (c) adoptable strategies of soil and water conservation, (d) integrated pest/disease/weed management through the use of biotic stress resistant germplasm with minimum pesticide/herbicide applications, (e) marketing strategies that are economically efficient, and (f) development of an appropriate policy and institutional environment that provides incentives to farmers to adopt legume-based BNF technologies.

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Implications of local soil knowledge for integrated soil fertility management in Latin America

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Abstract

The increasing attention paid to local soil knowledge in recent years is the result of a greater recognition that the knowledge of people who have been interacting with their soils for long time can offer many insights about the sustainable management of tropical soils. This paper describes two approaches in the process of eliciting local information. Case studies show that there is a consistent rational basis to the use of local indicators of soil quality and their relation to improved soil management. The participatory process used is shown to have considerable potential in facilitating farmer consensus about which soil related constraints should be tackled first. Consensus building is presented as an important step prior to collective action by farming communities in integrated soil management at the landscape scale. Taking advantage of the complementary nature of local and scientific knowledge is highlighted as an overall strategy for sustainable soil management.

Keywords: Collective action, Colombia, Honduras, landscape, natural resource management, participatory methodologies, Venezuela

Introduction

Local knowledge related to agriculture can be defined as the indigenous skills, knowledge and technology accumulated by local people derived from their direct interaction with the environment (Altieri 1990). It is the result of an intuitive integration of local agroecosystem responses to climate and land use change through time (Barrios et al. 1994). Transfer of information from generation to generation undergoes successive refinement leading to a system of understanding of natural resources and relevant ecological processes (Pawluk et al. 1992). WinklerPrins (1999) has provided a recent review of the scope and nature of the existing literature about local soil knowledge and the emerging science of ethnopedology.

There is increasing consensus about the need for enhanced understanding of local knowledge in planning and implementing development activities (CIRAN 1993). The slow rate of assimilation of new technology and new cropping systems has been often attributed to local inertia rather than the failures to take into account the local experience and needs (Warren 1991). According to Walker et al. (1995), increased application of indigenous knowledge to rural research and development can be attributed to the need to improve the targeting of research to address client needs and thus increase adoption of technological recommendations derived from research. Besides, ethical considerations related to participation and empowerment of local communities have gained considerable importance (Chambers 1983).

The complementary role that indigenous knowledge plays to scientific knowledge in agriculture has been increasingly acknowledged (Sandor and Furbee 1996). Experimental research is an important way to improve the information upon which farmers make decisions. It is questionable, however, if relying on experimental scientific methodology alone is the most efficient way to fill gaps in current understanding about the sustainable management of agroecosystems. There has been limited success of imported concepts and scientific interpretation of tropical soils in bringing desired changes in tropical agriculture. This has led an increasing recognition that the knowledge of people who have been interacting with their soils for long time can offer many insights about managing tropical soils in a sustainable way (Hecht 1990).

Nevertheless, although benefits of local knowledge include high local relevance and potential sensitivity to complex environmental interactions, without scientific input local definitions can sometimes be inaccurate and unable to cope with environmental change. It is thus argued that a joint local/scientific approach, capitalizing on complementarities and synergies, would permit overcoming the limitations of site specificity and empirical nature and allow knowledge extrapolation through space and time as suggested by Cook et al. (1998).

The science of ethnopedology encompasses many aspects, including indigenous perceptions and explanations of soil properties and soil processes, soil classifications, soil management, and knowledge of soil-plant inter-relationships (Talawar 1996). This paper examines three case studies on local soil knowledge and management and the implications of these results on future research on integrated soil management in Latin America. Results from case studies to elicit local information using key-informants are reported for small farmers from Orinoco floodplains in Venezuela and from the Cabuyal river watershed in Cauca, Colombia. A participatory approach was used with farmers from the Tascalapa river watershed in Yoro/Sulaco, Honduras, in order to identify and classify local indicators of soil quality related to permanent and modifiable soil properties. Finally, the potential of the latter approach as a mechanism to facilitate collective action leading to integrated soil management is discussed.

Case studies

Orinoco floodplain farmers from Venezuela

The local knowledge about soils and their management by Orinoco floodplain farmers was studied by Barrios et al. (1994). A case study approach with key-informants was used to highlight practices that lead floodplain farmers to high yields and economic success while improving or maintaining soil fertility (Anderson and Ingram, 1989, Brown et al., 1994). In this highly unpredictable environment, the basic assumption is that farmer's indigenous knowledge is the result of an intuitive integration of their perception of changes in the agroecosystem as a result of climatic changes, the major driving force for decision making. The systematic assessment of local knowledge about soils and their management focused on criteria used for selection of new agricultural sites in this typically slash and burn agriculture, for soil classification and soil texture "management" and for managing inherent soil variability.

In the Orinoco floodplains, when farmers are looking for new cropping land they make a first selection based on the type of vegetation growing on the soil. Therefore, traditional farmers use associations of native plants as indicators of soil quality. In order of importance, trees such as 'caujaro' (*Cordia sp.*), 'taparo' (*Crescentia sp.*) and 'yagrumo' (*Cecropia sp.*) and herbaceous species like 'gamelote' (*Paspalum fasciculatum*), 'paja de agua'(*Paspalum repens*), 'tarraya'(Glinus sp.) and 'borrajón' (*Heliotropium indicum*) were used as indicators of "good soils" (Table 1). Conversely, they also use native plants as indicators of where not to establish a cropping field. For instance, trees such as 'melero' (*Combretum frangulaefolium*) and 'toco' (*Crataeva gynandra*) as well as herbaceous species like 'yerbabuena' (*Phyla betulaefolia*) and the grasses 'pata colorada' and 'bochocha' were plants indicating "bad soils". It is not surprising that farmers use vegetation in their first evaluation of potential cropping sites since these integrate complex and often diffuse soil attributes.

Once the agricultural plot has been selected a more detailed examination of the soil allows farmers to plan crop and soil management activities. While darker colored soils are generally recognized as better soils, local farmers identified soil texture as the most important measure on which to select crop and soil management practices. Farmers recognized the importance of fine texture sediment in floodplain soil fertility. Given the great uncertainty of sediment quality every year as influenced by flooding regimes, a traditional system to manage the quality of the incoming sediments was developed by floodplain farmers (Barrios et al., 1994). Vegetation barriers are allowed to grow or are planted by farmers around their agricultural plots in order to "filter" the coarse sediment and only allowing the finer sediment into the plots. Vegetation barriers are typically composed of trees like ‘Jariso’(*Ruprectia sp.*), ‘guayabo rebalsero’ (*Psidium ovatifolium*) and grasses like ‘gamelote’(*P. fasciculatum*) (Fig.1).

Table.1 Most important plant species used as local indicators of soil quality by Orinoco floodplain farmers (modified from Barrios et al., 1994)

Common name	Scientific name	Botanical family	Plant type**	Soil type
Gamelote	Paspalum fasciculatum	Gramineae	H	Fertile
Paja de agua	Paspalum repens	Gramineae	H	
Tarraya	Glinus sp	Aizoae	H	
Borrajón	*Heliotropium sp.*	Boraginaceae	H	
Caujaro	*Cordia sp..*	Boraginaceae	T	
Pira	*Amaranthus dubius*	Amaranthaceae	H	
Taparo	*Crecentia cujete*	Bignoniaceae	T	
Yagrumo	*Cecropia sp*	Moraceae	T	
Artemisa	*Ambrosia cumanensis*	Asteraceae	H	
Granadilla	*Polycarpea sp.*	Caryophylaceae	H	
Melero	*Combretum frangulaefolium*	Combretaceae	T	Poor
Toco	*Crataeva gynandra*	Capparidaceae	T	
Yerbabuena	*Phyla betulaefolia*	Verbenaceae	H	
Pata colorada	*s.n.n.i.**	Gramineae	H	
Bochocha	*s.n.n.i.**	Gramineae	H	

* s.n.n.i. = scientific name not identified
** Plant type: H = herbaceous, T = tree.

Soil heterogeneity is very conspicuous because of the uneven distribution of sediment throughout the floodplain. The use of different crops in areas with different soil texture by traditional farmers shows an optimization of soil resource use. This could be seen as a traditional basis for modern site-specific management. Local wisdom indicates that while certain crops only grow well in specific soil textures, e.g., watermelon in sandy soil, beans in clay soil and cotton in mixed soil, other crops such as maize and cowpea are ubiquitous and are found in all soil textures (Barrios 1997).

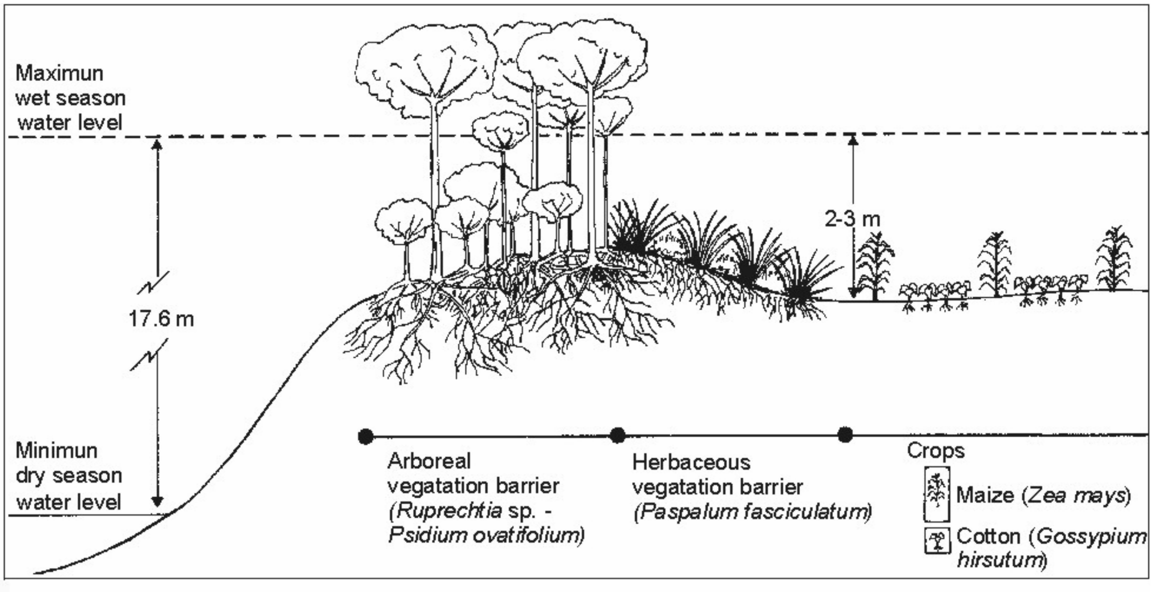

Figure 1. Schematic diagram of vegetation barriers used by Orinoco floodplain farmers to manage the quality (particle size) of the incoming sediment into their agricultural plots (modified from Barrios et al., 1994).

Andean hillside farmers from Colombia

Studies on local knowledge about soils and their management were conducted within the Cabuyal watershed, Cauca department – Colombia using case study approaches with semi-structured questionnaires, participatory farm mappings of soil qualities and identification of local indicators used to discriminate among different soils (Trejo *et al.* 1999). Previous studies in the area by CIAT (Centro Internacional de Agricultura Tropical) during the last 15 years facilitated the identification of key informants from each village. Key informants were selected from eight villages in three altitudinal zones in the watershed (Salamanca 2000). High elevation villages (1700-2200 m.a.s.l.) included: El Cidral, La Esperanza, La Primavera and El Rosario, middle elevation villages (1450-1700 m.a.s.l.) La Campiña and El Porvenir, and low elevation villages (1175-1450 m.a.s.l.) included La Llanada and La Isla. In the predominantly young volcanic-ash soils, Oxic Dystropepts in the USDA soil classification system, 100% of farmers interviewed use soil color for classification and assessment of soil quality. Black colored soils are considered good for cropping and yellow and red soils are considered marginal. Black soils are often found in soils under forest, fallow or pastures. Increasing use of tillage has lead to increased rates of soil loss and thus the usually darker topsoil has given way to the red sub-soil where cultivation is now taking place in many agricultural plots.

Native plants constitute another means by which Andean hillside farmers classify the soils in their farms (Barrios and Escobar, 1998). In Table 2 we find native plants used as indicators of soil quality by farmers in the Cabuyal river watershed. Fertile soils are characterized by trees like ‘nacedero’ (*Trichanthera gigantea*) and ‘guamo’ (*Inga sp*.) and herbaceous plants like ‘papunga’ (*Bidens pilosa*) and ‘mariposo’(Clibadium surinamensis) while plants predominating in poor soils invariably include ‘helecho marranero’ (*Pteridium arachnoideum*) and ‘paja garrapatera’ (*Andropogon bicornis*). Farmers also identify ubiquitous species such as ‘yaraguá’ (*Mellinis minutiflora*) and ‘caracola’ (*Koheleria lanata*) which are then characterized by their vigor and leaf color. Darker green colored leaves are associated with more fertile soils while yellowish colors are indicative of poor soils.

Table. 2 Most important plant species used as local indicators of soil quality by Cabuyal watershed hillside farmers, Colombia (modified from Barrios and Escobar 1998).

Common name	Scientific name	Botanical family	Plant type**	Soil type
Papunga	*Bidens pilosa*	Asteraceae	H	Fertile
Mariposo	*Clibadium surinamensis*	Asteraceae	H	
Margarita	*Chaptalia nutans*	Asteraceae	H	
Mortiño	*Clidemia hirta*	Meliaceae	H	
Altusara	*Phytolacca americana*	Phytolaccaceae	H	
Siempre Viva	*Commelina difusa*	Commelinaceae	H	
Hierba de chivo	*Ageratum conyzoides*	Asteraceae	H	
Nacedero	*Trichantera gigantea*	Acanthaceae	T	
Cachimbo	*Erythrina sp*	Leguminosae	T	
Guamo	*Inga sp*	Leguminosae	T	
Helecho marranero	*Pteridium arachnoideum*	Pteridiaceae	H	Poor
Paja garrapatera	*Andropogon bicornis*	Poaceae	H	
Paja blanca	*Andropogon leuchostachys*	Poaceae	H	
Helechillo	*Dichranopteris flexosa*	Pteridaceae	H	
Yaraguá	*Mellinis minutiflora*	Poaceae	H	Any soil
Caracola	*Koheleria lanata*	Gesneriaceae	H	

** Plant type: H = herbaceous, T = tree.

Soils are also classified by their structure into ‘polvoso’ or “powdery”, that is, with no macroaggregates indicating degraded soils on the one hand, and ‘granoso’ or “grain-like” which indicates some level of aggregation associated with better soils. This is an important characteristic used by farmers to assess soil recuperation after degraded soils have been left uncultivated to “rest” or fallow. In these hillside soils, topographic position also plays an important role in local soil classification. Hill tops or ‘cimas’are identified as containing poorer soils, while the quality of hillsides or ‘lomas’ depends on how steep is the slope is. The more fertile soils are concentrated in the flat areas or ‘planadas’, hollowed areas or ‘huecadas’ because of the accumulation of eroded soils lost from up the hill as well as riverine floodplains by deposition of nutrient rich sediments (Cerón 2000). Inherently infertile soils are named ‘tierra brava’ or “angry soils” which should be distinguished from ‘tierra cansada’ or “tired soils” which are soils degraded by inappropriate management. Farmers consider that while the former are likely to respond to fertilizer applications (i.e. chicken manure) the latter invariably needs a period of fallow phase to recover lost attributes.

Central American hillside farmers from Honduras

A participatory approach was used in Honduras to identify and classify local indicators of soil quality and details can be found in Trejo et al. (1999). In short, six communities were selected from the Tascalapa watershed, namely Santa Cruz, Mina Honda (higher zone), San Antonio, Jalapa and Luquigue (middle zone) and Pueblito (lower zone) to identify and classify local indicators of soil quality at a landscape scale. Brainstorming sessions with farmer groups from the six communities respectively were followed by a prioritization phase where farmers from each community were split in smaller groups in order to rank local soil quality indicators identified according to their relative importance using paper cards. The final list of local indicators, in order of importance, was then integrated with their corresponding technical indicator in plenary sessions and organized into indicators of permanent (Tables 3) and modifiable (Table 4) soil properties.

Although some local indicators can be rather general like fertility, slope, productivity and age under fallow, other local indicators are more specific. For instance, plant species growing in fallows, soil depth, color, water holding capacity and predominant soil particle sizes provide indicators that can be easily integrated with technical indicators of soil quality.

The classification of local indicators into permanent and modifiable factors provides a useful division that helps to focus on those where improved management could have the greatest impact. This strategy is particularly sound when there is considerable need to produce tangible results in a relatively short time in order to maintain farmer interest as well as to develop the credibility and trust needed for wider adoption of improved soil management practices.

Key permanent soil properties captured by local indicators that are commonly perceived as important by farming communities included slope, soil depth, soil color, soil texture and soil structure. The importance of slope in this hillside environment is obvious as there is a maximum inclination under which agriculture can be practiced. Because of their topography, hillside soils are prone to erosive processes even under natural vegetation or appropriate management. These soils tend to be relatively shallow compared to valley soils and therefore local farmers identify a minimum soil depth required for crop root growth and development (i.e. 12 inches, half a cutlass). Soil color provides a good measure of inherent soil fertility where black soils are seen as good soils and other red and yellowish colors as bad soils. Nevertheless, despite being classified as a permanent property, local farmers recognize that management practices involving crop residue additions could darken light colored soils indicating improvement in their quality. Soil texture is considered important by local farmers because it affects soil water holding capacity as well as the resistance to tillage. Soil workability is also related to soil structure, as good soils are perceived as those that do not compact, and where soil aggregates can be broken by tillage.

Modifiable soil properties of importance were perceived as those related to the lack or presence of burning, the type of native vegetation and the soil biological activity indicated by the presence of soil organisms (i.e. earthworms). The earliest farmers have used fire as an agricultural management tool to recover nutrients held in the native vegetation biomass for the crops, to control pests and to dispose of perceived “excess” plant biomass in the fields (Sanchez, 1976). Despite the realization of the harm done by annual fires on the soil, the lack of farmer consensus that could lead to a concerted action appears to be an important limitation. The participatory methodologies presented here have the potential to facilitate consensus amongst the local farmer community on high priority problems and opportunities. In this capacity, their linkage to concrete plans of action, as explained by Thomas et al. (2000), suggests this approach as a way to promote collective action at a landscape scale. A similar rationale has been successfully used in Africa to stimulate the participatory learning and action research process by Defoer and Budelman (2000).

It is important to note that the type of native vegetation present in a soil is a local indicator of soil quality (Table 5) that not only cuts across the communities studied in Honduras but also across the other two case studies reported in this article. This observation suggests that there may be an underlying fundamental ecological principle behind farmer observations in the three locations. It is proposed here that one such ecological principle is that of natural succession as suggested by Paniagua et al. (1999). Natural and agricultural ecosystems respond similarly to degradation or regenerative processes through natural succession.

Table 3. Integration of local and technical indicators of soil quality related to permanent soil properties identified and ranked according to their importance by Honduran hillside farmers from different villages (adapted from Turcios et al., 1998).

	Knowledge Integration					
Ranking	Santa Cruz	Mina Honda	Jalapa	San Antonio	Luquigue	Pueblito
1	High water retention/ low water retention. (Texture/ water holding capacity)	Spongy, “espolvoreado”, not sticky/”Arenisca”, hard, sticky. (Texture)	Thick soil layer/thin soil layer. (Soil depth)	Deep or thick soil/ thin soil. (Soil depth)	Soil thickness of at least 12 inches, 2 palms, half a cutlass/thin soil less than 4 inches. (Soil depth)	Flatlands/ “Tierras quebradas” broken lands. (Slope)
2	Thick top soil/thin top soil. (Soil depth)	Soil with a thick fertile layer/ ”frierra”, when fertile layer is very thin or absent. (Soil depth)	Soils with gentle slopes, uniform/soils with high slopes. (Slope)	Black color/Light color, yellowish, reddish. (Color)	Good holding of water, soil that absorbs water/ low water retention. (Texture/water holding capacity)	Thick soil layer/thin soil layer, “delgadita”. (Soil depth)
3	Blackish/light colors. (Color)	“Tierra tendida”, “poca falda”, little slope/”Guindo”, “abismo”, steep slopes. (Slope)	Soil keeps water for longer time/soil does not keep water. (Texture/water holding capacity)	Good plow penetration/limited plow penetration. (Physical barriers)	Easy to plow/difficult, needs skill to plow. (Physical barriers)	“Harinita”, flour like, “huestesita”/ clay soil, sandy soil. (Texture)
4	Flatter lands/“Tierras quebradas”, broken lands. (Slope)	Black color/”colorada”, reddish, “amarilla”, yellowish. (Color)	Black/various soil colors. (Color)	Few stones/plenty of large stones or “lajas”. (Stoniness)	Black color/Yellow color, “moreno”, tan, “colorada”, reddish. (Color)	Black soils/Reddish soils, “medias coloradas”. (Color)
5	Many stones/few stones. (Stoniness)	“Suelos francos”, loamy soils/ “barriales”,clay, mud, “arenoso”, sandy. (Texture)	Fast water absorption/ slow water absorption, (Texture/infiltration)	Little slope/steep slope or “falda”. (Slope)	Loose rocks on topsoil, not many stones/knowledge of rocks below topsoil by inserting machete. (Stoniness)	Could have small stones/have big stones. (Stoniness)
6		Small stones and few/ Many stones. (Stoniness)	Loamy soils, little clay/ “Brarrialosa”or muddy, sandy. (Texture/particle size)	Loams “francos”/ “Barrialosa”, muddy, much sand. (Texture)	“Suelos francos”, loamy soils/”areniscas”, sandy soils, “barrilosas”or clay soils. (Texture)	“No se ende”, not a cracking soil/”Se ende”, cracking soil. (Clay type)
7			Easy tillage/difficult tillage, “Tronconosa”. (Physical barriers)	“No se ende”, non-cracking soils/”Se ende”, cracking soils. (Clay type)	“No se ende”, non-cracking soils/”Se ende”, cracking soils. (Clay type)	
8			No stones present/ “Balastrosa”, stony, gravely. (Stoniness)			

Table 4. Integration of local and technical indicators of soil quality related to modifiable soil properties identified and ranked according to their importance by Honduran hillside farmers from different villages (adapted from Turcios et al. 1998).

	Knowledge Integration					
Ranking	Santa Cruz	Mina Honda	Jalapa	San Antonio	Luquigue	Pueblito
1	Fertile soil / Non-fertile soil. (Fertility)	“Revenideros”, washed land, “tierra lavada”/ “Tierra no lavada”, unwashed land. (Erosion)	“Opulento”, no need of chemical fertilizer/ needs fertilization. (Soil fertility)	“Opulento”, high fertility / low fertility. (Soil fertility)	Good plants, good crop, lush and thick plants / Bad plants, bad crops. (Vegetation type / Yield)	Soil is not poddled, “no se aguachina”/soil is poddled, “se aguachina” (Drainage)
2	Organic residue in-corporation of organic residues. (Soil organic residues)	Good yields given/Bad yields given. (Yield)	Presence of earth-worms/lack of earthworms. (Biological activity)	“Verdolaga”, “quilete”, “chichiguaste”, “chango”, “Pica pica”, “guama” / “tatascán”, “Pino”. (Indicator plants)	Land with “chichiguaste” and malva/land with “zacate” or native pasture. (Indicator plants)	Soil incorporated/ washed soil. (Erosion)
3	“Tierra blanda”, soft soil, “suelta”, loose/ “Tierra amarrada”, tied soil. (Structure)	“Buenos guamiles”, good fallows, / “Rastrojito”, “bajillales”, small fallows (Vegetation type)	Soil macroaggregates can be broken into pieces, “suelo suelto”, loose soil/Macroaggregates can not be broken, “suelo amarrado”, tied soil. (Structure)	High yields/low yields. (Yields)	“Porosita”, “despolvorienta”, loose soil, “se desparrama”, non-compacted / No se desparrama, compacted. (Structure)	“Tierra se espolvorea”, soil is not compacted/ soil compacts as balls, “se amarra”, it is tied up. (Structure)
4	Good weed growth/ poor weed growth. (Type of vegetation)	“Terronosa”, aggregated, “suelta”, loose/”Masiva”, compacted. (Structure)	No burnings have occurred in the last 5 years/Lands have been burned in the last 5 years. (Soil burning)	Without “manto” or incorporating decomposing residues/ with “manto”. (Soil organic matter)	New land use<10 yrs, from pasture to crop-land, land from ancestors was good/ old land, greater than 10 years of use. (Length of current land use)	Does not occupy fertilizer/needs fertilizer. (Fertility)
5	No burning/burning. (Soil burning)	Soil with a black layer/ Soil with litter or without black layer. (Soil organic matter)	“Zaléa”, “Chichiguaste”/ “Chichiguaste” does not grow, weeds do not develop, “zacate de gallina” (Indicator plants)	“Suelta”, loose, “suave”, soft, “terronosa”, large aggregates/”Tablones”, laminar structure. (Structure)	No burning/burning (Soil burning)	No burning/burning (Soil burning)
6		No burning/burning. (Soil burning)	Greater yields/Lower yields, more work to produce. (Yield)	No burning/burning. (Soil burning)	“Manto”, organic residues incorporated into the soil/ ”Manto” not incorporated. (Soil organic matter)	

Table 4. Contd..

	Knowledge Integration					
Ranking	Santa Cruz	Mina Honda	Jalapa	San Antonio	Luquigue	Pueblito
7			Soil does not flood, no “aguachina”/ “aguachina”, “sweaty” soil. (Drainage)	“No se aguachina”, does not flood/”Se aguachina” gets muddy, water does not filter through. (Drainage)	Soil does not fill with water, “No se empapa”/soil fills with water, “Se empapa”, “pichera”. (Drainage)	
8			Non washed soils/ washed soils (Erosion)		Crops grow with little or no fertilizer/only growth with fertilizer. (Fertility)	
9					Un-washed land/ washed land. (Erosion)	

The most adapted plants and organisms in the soil gradually replace less adapted ones as continued selective pressures are exerted (i.e. during regeneration of soil fertility or soil degradation). Native plants and "weeds", as biological indicators, have the potential to capture subtle changes in soil quality because of their integrative nature. They reflect simultaneous changes in physical, chemical and biological characteristics of the soil. There is considerable scope, therefore, to further explore the use of local knowledge about native plants as indicators of soil quality and as a tool guiding soil management decisions.

Table. 5 Most important plant species used as local indicators of soil quality by Tascalapa watershed hillside farmers, Honduras (modified from Turcios et al. 1998)

Common name	Scientific name	Botanical family	Plant type**	Soil type
Chichiguaste	Eletheanthera ruderalis	Asteraceae	H	Fertile
Verdolaga	*Portulaca oleraceae*	Portulacaceae	H	
Malva	*Anoda cristata*	Malvaceae	H	
Zalea	*Calea urticifolia*	Asteraceae	H	
Guama	*Inga sp.*	Fabaceae	T	
Quilete	*Phytolaca icosandra*	Phytolaccaceae	H	
Pica pica	*Mucuna pruriens*	Fabaceae	H	
Zacate de gallina	*Cynodon dactylon*	Gramineae	H	Poor
Tatascán	*Perymenium nicaraguense*	Asteraceae	H	
Pino	*Pinus caribeae*	Pinaceae	T	

** Plant type: H = herbaceous, T = tree

Implications for integrated soil management across the landscape

Farmers are often more enthusiastic to empirical approaches (i.e. local knowledge, on-farm experiments) than prescriptive approaches (i.e. scientific knowledge, recipes for soil management) (Cook *et al*., 1998). Figure 2 illustrates that while scientific information can be very precise its relevance can be relatively low. On the other hand, while local information can be relatively imprecise, yet, it can be very relevant. Although information should ideally be certain in both meaning and context, in reality this is not the case. Research efforts should further explore a suitable balance between precision and relevance as seen in the figure.

The methodological approach proposed by Trejo et al. (1999) goes beyond the identification and classification of local indicators of soil quality. It rests on the hypothesis that in order for sustainable management of the soil resource to take place, it has to be a result of improved capacities of the local communities to better understand agroecosystem functioning. Improved capacities by technical officers (extension agents, NGO's, researchers) to understand the importance of local knowledge is also part of the methodology. Therefore, after identifying if there is poor or a lack of adequate communication between the technical officers and the local farm community as a major constraint to capacity building, the methodology proposed deals with ways of jointly generating a common knowledge that is well understood by both interest groups. The structure of the guide is shown in Fig.3 shows the different sections of the methodological guide.

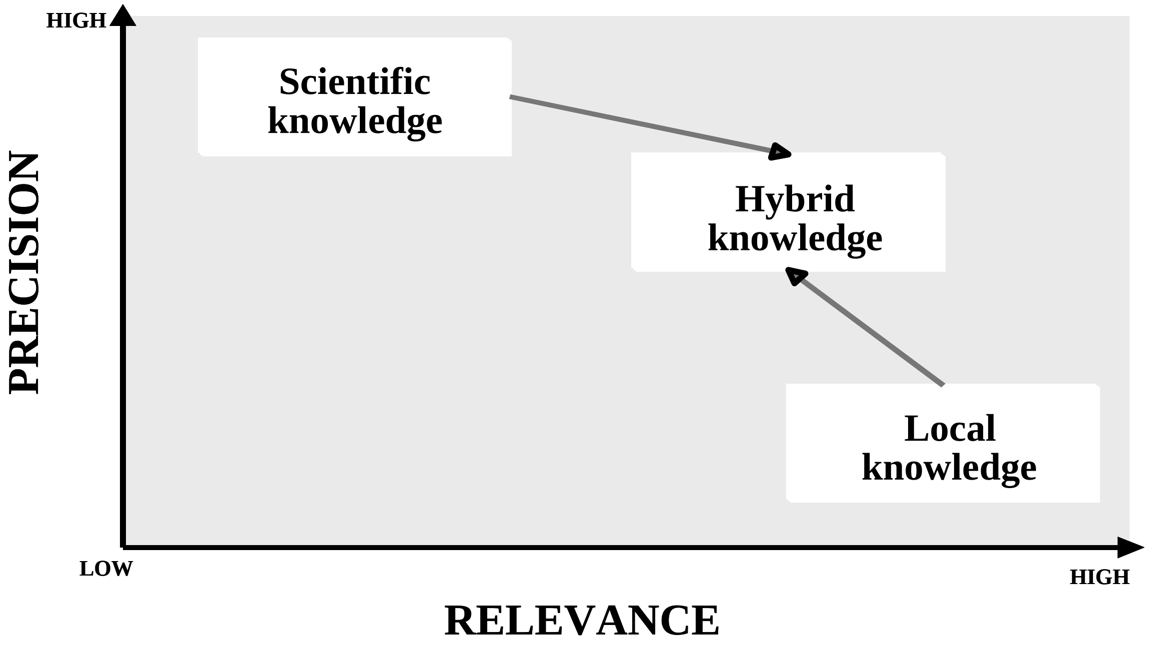

Figure 2. Schematic representation of the comparison between scientific and local knowledge systems

Section 1, which provides a general overview of soil formation factors and processes, based on Jenny's seminal work (Jenny, 1941, 1980), is presented in order to bring the trainees (e.g. technical officers) to a common starting point. Section 2 deals with participatory techniques that help gather, organize and classify local indicators of soil quality through consensus building. Section 3 attempts to find correspondence between local indicators and technical indicators. This is carried out in a plenary session exercise of integration where the most important local indicators of soil quality are analyzed in the context of technical knowledge and are classified into indicators of permanent or modifiable soil properties. The idea is to provide a guideline to focus efforts on soil properties where management can have an impact. An important part of this section is the Soils Fair for farmers that is organized by the trainees. The Fair aims to help farmers develop skills to characterize relevant physical, chemical and biological properties of their soils through simple methods that can then be related to their local knowledge about soil management.

The result of this two-way exchange process has a positive impact on the technical knowledge by nurturing it with local perceptions and demands. The number of successful experiences in natural resource management in agroecosystems will likely increase because of the solid basis provided by local relevance. On the other hand, local knowledge will also be enriched because of greater possibilities for its wider comprehension, appreciation and use. Local communities will be empowered by the joint ownership of the technical-local soil knowledge base constructed during this process.

The two-way improvement of communication channels will likely improve the communication of farmer's perceptions to extension agents and researchers as well as make recommendations by extension agents and NGOs better understood by the farmer community. Better communication opens opportunities for established and/or emerging local organizations to use the methodological approach for consensus building that precedes any collective actions for improved natural resource management through integrated soil management.

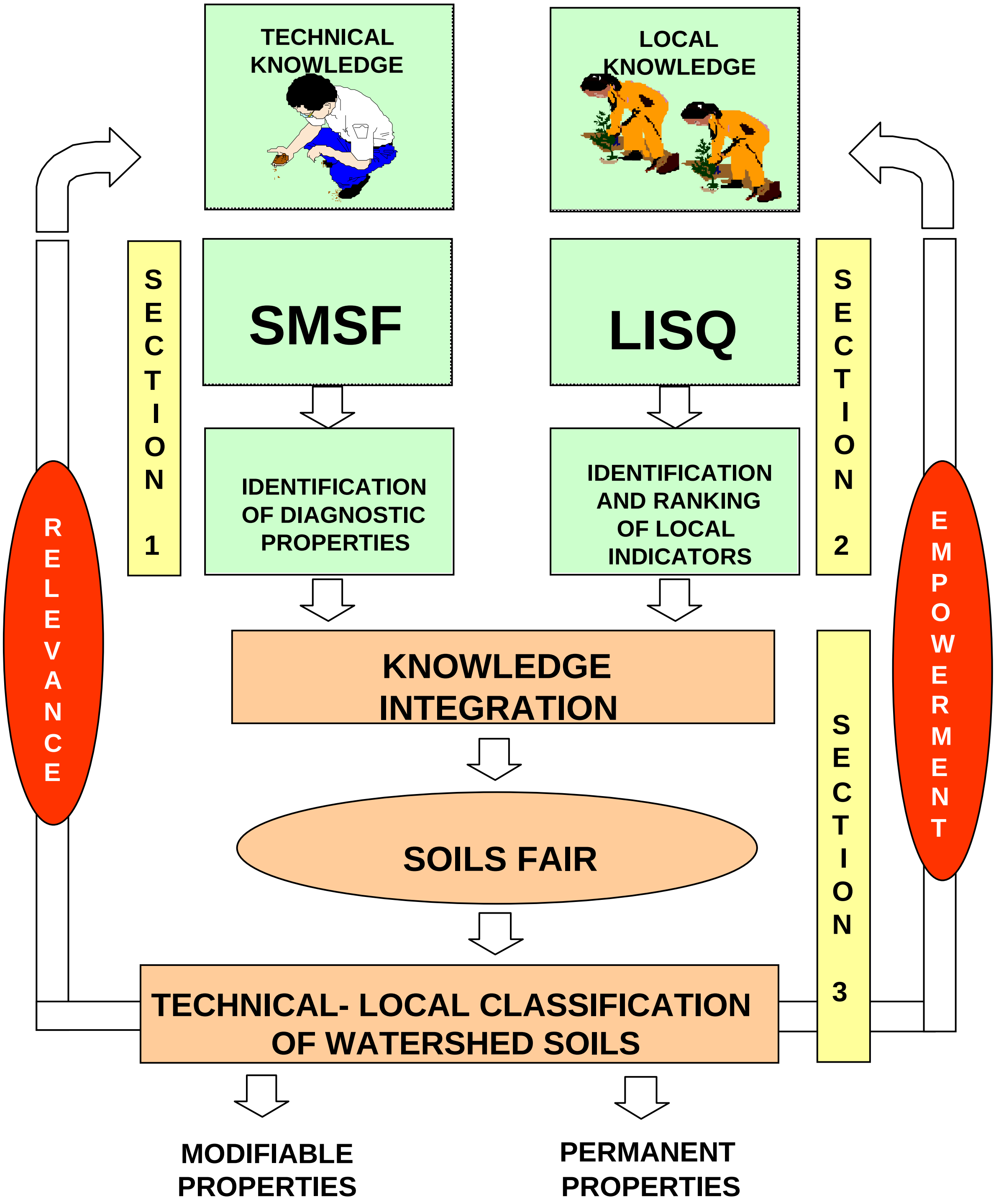

Figure 3. Structure of the methodological guide for the participatory identification and classification of local indicators of soil quality (Adapted from Trejo et al. 1999).

Conclusions

The considerable importance of local knowledge in guiding future research and development efforts towards a sustainable management of natural resources is highlighted in this study. The case studies presented showed that there is a consistent rational basis to the use of local indicators of soil quality. The use of key-informants was an effective method to elicit local information about soils and their management. In addition, participatory approaches involving group dynamics and consensus building are likely to be key to improve soil management beyond the farm-plot scale to the landscape scale through the required collective action process.

Native plants as local indicators of soil quality were important local indicators of soil quality in all three case studies associated with modifiable soil properties. The use of indicator plants, belonging to the local knowledge base, when related to management actions could ease adoption of improved technologies. This approach would allow the use of plants as indicators of soil quality to which local farmers can relate more closely than to common agronomic measures such as phosphorus availability, organic matter content or pH value. Additional research could also include further integration of scientific spatial analysis (i.e. GIS, topographic modeling) with the spatial perception of natural resources by farmers aiming at improved implementation of site-specific management.

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Decomposition and nutrient release by green manures in a tropical hillside agroecosystem

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Keywords: *in vitro* dry matter digestibility, nutrient release, residue management, resource quality, weight loss

Abstract

The decomposition and nutrient release of 12 plant materials were assessed in a 20-week litterbag field study in hillsides from Cauca, Colombia. Leaves of *Tithonia diversifolia* (TTH) and *lndigofera constricta* (IND) decomposed quickly (k=0.035±0.002 d^{-1}), while those of *Cratylia argentea* (CRA) and the stems evaluated decomposed slowly (k=0.007±0.002d^{-1}). Potassium presented the highest release rates (k>0.085 d^{-1}). Rates of N and P release were high for all leaf materials evaluated (k>0.028 d^{-1}) with the exception of CRA (N and P), TTH and IND (P). While Mg release rates ranged from 0.013 to 0.122 d^{-1}, Ca release was generally slower (k=0.008-0.041 d^{-1}). Initial quality parameters that best correlated with decomposition (P<0.001) were neutral detergent fibre, NDF (r=-0.96) and *in vitro* dry matter digestibility, IVDMD (r=0.87). It is argued that NDF or IVDMD could be useful lab-based tests during screening of plant materials as green manures. Significant correlations (P<0.05) were also found for initial quality parameters and nutrient release, being most important the lignin/N ratio (r=-0.71) and (lignin+polyphenol)/N ratios (r=-0.70) for N release, the C/N (r=-0.70) and N/P ratios (r=-0.66) for P release, the hemicellulose content (r=-0.75) for K release, the Ca content (r=0.82) for Ca release, and the C/P ratio (r=0.65) for Mg release. After 20 weeks, the leaves of *Mucuna deerengianum* released the highest amounts of N and P (144.5 and 11.4 kg ha^{-1}, respectively), while TTH released the highest amounts of K, Ca and Mg (129.3,112.6 and 25.9 kg ha^{-1}, respectively). These results show the potential of some plant materials studied as sources of nutrients in tropical hillside agroecosystems.

Introduction

Hillsides of tropical America cover about 96 million hectares (Jones, 1993) and have important roles as reserves of biodiversity and source of water for areas downslope (Whitmore, 1997). A high proportion of the Colombian Andean soils (i.e. 83%) suffer from erosion problems (Amezquita et al., 1998). These soils, particularly the volcanic-ash soils, usually contain high levels of soil organic matter (SOM) but low availability of nutrients due to SOM protection by mineral particles which limits decomposition (Phiri et al., 2001). According to Shoji et al. (1993) plant growth in volcanic-ash soils is limited by the low availability of N and P together with low base saturation and deficiency of some micronutrients (Cu, Zn and Co).

Use of green manures could reduce soil exposure to erosive processes, promote a greater nutrient cycling and improve the synchrony of nutrient release with crop demand. However, the potential benefit of green manures as a source of nutrients to crops can only be achieved if their decomposition and nutrient release patterns are known so that the synchrony of nutrient release with crop nutrient demand can be improved (Myers et al., 1994). Management options include the selection of plant materials with different chemical composition (quality) and by controlling the timing, quantity and form of application to the soil (Anderson and Ingram, 1993; Palm, 1995; Palm et al., 2001). Besides, the single or combined applications of plant parts used as green manures (i.e. leaves, stems) are likely to influence the decomposition and nutrient release rates to the soil (Lehmann et al., 1995; Handayanto et al., 1997).

Several methods have been used to determine decomposition and nutrient release of plant materials in the field, and the litterbag technique is probably the most widely used because of its simplicity, replicability, and ability to selectively exclude classes of soil fauna (Vanlauwe et al., 1997a). However, while this method may underestimate dry matter and nutrient losses it is considered a great tool for treatment comparisons (Vanlauwe et al., 1997a and b). For this technique, standard quantities of litter are enclosed in nylon-mesh bags; litterbags are then incubated in the field, and weight and nutrient loss are monitored during several weeks by partial retrieval of litterbags.

The quality of plant materials has been considered one of the most important factors that affect decomposition and nutrient release (Heal et al., 1997; Swift et al., 1979). High nutrient contents in plant materials have generally been correlated with high decomposition rates (Gupta and Singh, 1981). Other researchers have found that low lignin/N ratio (L/N) also leads to faster decomposition (Melillo et al., 1982). According to Palm and Sanchez (1990), polyphenol (PP) concentrations can influence decomposition and nutrient release rates in legume materials to a greater extent than lignin (L) or N content. Furthermore, Thomas and Asakawa (1993) reported that the C/N, L/N, PP/N and (L+PP)/N ratios were all inversely correlated with N release rates from herbaceous materials; while weight loss only correlated with the L/N and (L+PP)/N ratios. More recent studies also showed similar correlations between the (L+PP)/N ratio and decomposition and N release for several agroforestry species (Barrios et al., 1997; Lehmann et al., 1995; Mafongoya et al., 1998; Vanlauwe et al., 1997b). Tian et al. (1996), on the other hand, showed that decomposability of plant residues placing nylon-mesh bags inside the rumen of fistulated animals significantly correlated with that using litterbags in the field. Using a similar principle, another promising plant quality index is the in vitro dry matter digestibility (IVDMD) lab test used for animal feed (Harris, 1970). Although the decomposition processes in the rumen and the soil differ, they are sufficiently similar to be thought of as a potential method for comparative plant tissue studies (Chesson, 1997).

In this study we determined the decomposition and release of N, P, K, Ca and Mg by 12 plant materials used by farmers in our study areas. These plant materials were surface applied to a soil in a tropical hillside agroecosystem, and we assessed the relationship of some common plant quality indices and IVDMD for such materials to their respective decomposition and nutrient release rates.

Materials and methods

Site description

The study was carried out at 'San Isidro' experimental farm located in Pescador, Cauca department, Colombia, at 2° 48' N, 76° 33' W and 1.500 masl. The area has a mean temperature of 19.3 ^{o}C and a mean annual rainfall of 1900 mm (bimodal). The experiment was conducted from April to August during the first cropping season of 1998 (Figure 1).

The experimental plot had a slope of approximately 30%. The soils, derived from volcanic ashes, have been classified as Oxic Dystropepts (Inceptisols) in the USDA soil classification system (USDA, 1998). Soil characteristics include: pH (H_20): 5.1,50 9 kg^{-1} C, 3 9 kg^{-1} N, 4.6 mg kg^{-1} soil of Bray-II P, and 1.1, 0.6, 2.5 and 0.9 cmol kg^{-1} soil of Al, K, Ca and Mg, respectively. Soil bulk density was 0.8 g cm^{-3} and allophane content ranged from 52 to 70 g kg^{-1} (Phiri et al., 2001).

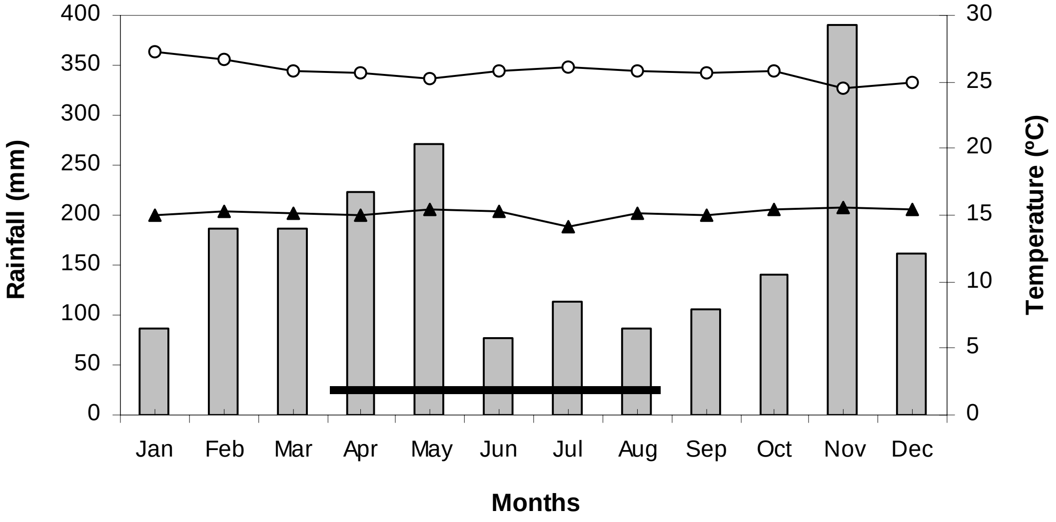

Figure 1. Monthly rainfall (bars) and maximum (o) and minimum (▴) air temperature (°C) at San Isidro Farm, Pescador, Cauca (Colombia), during 1998. The horizontal bar indicates the experimental period.

Selected plant materials

Plant materials were selected from plants with known adaptation to the hillside environment and also with contrasting quality. Since two species and three varieties of Mucuna are utilized by farmers in our study areas and they show differences in agronomic behaviour it was considered important to evaluate their decomposition and nutrient release rates. Plant materials included: leaves, with petioles, of *Canavalia brasiliensis* Mart. ex Benth. (CAN), *Cratylia argentea* Benth. (CRA), *lndigofera constricta* Rydb. (IND), *Mucuna deerengianum* (Bort.) Merr. (MDEE), *Mucuna pruriens* (Stick.) DC. var. IITA-Benin (MPIT), *Mucuna pruriens* (Stick.) DC. var. Tlaltizapan (MPTL), *Mucuna pruriens* (Stick.) DC. var. Brunin (MPBR) and *Tithonia diversifolia* (Hems.) Gray (TTH); stems (<1 cm width) of *Mucuna pruriens* var. IITA-Benin (MPITs) and *lndigofera constricta* (INDs); and a mixture of stems and leaves of *Mucuna pruriens* var. IITA-Benin (MPITm) and *Indigofera constricta* (INDm), in the proportion found at the time of pruning and collection. Stems and the mixture of leaves and stems were studied to relate to common farmer practice of mixed application. It also contributed to expand the quality spectrum of materials evaluated and to compare them with the leaves alone. Pruned materials were collected from herbaceous plants (*Canavalia* and 'Mucunas') and *Tithonia* at flowering, while materials from trees (*Cratylia* and *Indigofera*) were pruned 6 months after the last pruning. Harvest time for herbaceous materials followed farmer practices and for tree materials was associated with optimal pruning regime identified in previous unpublished studies.

Experimental design

After collection, each plant material was air and oven dried (60 °C), thoroughly mixed and composited, and a sample was taken for chemical analyses. Then, 15 g of each plant material were placed inside litterbags (20x20 cm nylon bags, mesh size 1.5 mm), corresponding to an application rate of 3.75 Mg dry matter ha^{-1}. Litterbags were placed on the soil surface between maize rows in a randomized complete block design with four replications. The maize crop did not receive any additional treatments besides residue quality. At 2, 4, 8, 12 and 20 weeks, one litterbag of each repetition and treatment was collected, manually cleaned, and washed with distilled water to remove soil particles. Remaining plant material was air and oven dried (60 °C) to constant weight before determining dry weight and nutrient contents.

Chemical characterization of plant materials

Subsamples of plant materials used in litter bags were analyzed for their in vitro dry matter digestibility (IVDMD), total carbon (C), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and contents of acid detergent fibre (ADF), neutral detergent fibre (NDF), hemicellulose (HEM), lignin (L), polyphenols (PP) and N fixed to ADF (N-ADF). In addition, the amount of plant material retrieved from litterbags at each sampling time was analyzed for total N, P, K, Ca, Mg and ash content.

All plant material was ground and passed through a 1-mm mesh before analysis. C, N and P were determined colorimetrically with an autoanalyzer (Skalar Sun Plus, Breda, The Netherlands), and K, Ca and Mg with an atomic absorption spectrophotometer (Unicam 969, Reading, U.K.). ADF, NDF and lignin were determined using modified techniques of Van Soest and Vine (Harris, 1970) and total polyphenols with a modified Anderson and Ingram (1993) method that uses 70% methanol, 0.5% formic acid and 0.05% ascorbic acid as extractant (Telek, 1989), the Folin-Ciocalteu reagent and tannic acid as standard. HEM was calculated by substracting ADF from NDF. IVDMD was determined by the modified methodology of Tilley and Terry, that includes a 48-h incubation of plant materials with rumen microorganisms followed by acid/pepsine digestion (Harris, 1970). Ash contents were determined by heating at 550 °C for 2 h and these data were used to correct the weight of the plant material remaining for contamination with soil.

Calculations and statistical analysis

Decomposition of plant materials and their N, P, K, Ca and Mg release were evaluated through assessment of dry weight and nutrient losses from the materials. The percent of dry weight remaining (DWR), and nutrients remaining (NR, PR, KR, CaR and MgR), for each experimental unit, was calculated as shown:

$$XR(\%) = (Xt/Xo) \times 100,$$

where XR is the percent weight or nutrient remaining, Xt the weight or nutrient content at each sampling time and Xo the starting weight or nutrient values. Dry weight and nutrients remaining were subjected to analysis of variance (ANOVA) at each sampling time. Standard errors of the difference in means (SED) were calculated from the ANOVA and reported with the data. Whenever necessary, variables were log-transformed to normalize data.

In order to describe treatment trends, treatment means of dry weight and nutrients remaining were regressed over time using a single exponential decay model (Wieder and Lang, 1982). This model is described by the following equation:

$$XRt = 100.\ \exp^{-kt},$$

where XRt is the dry weight or nutrient remaining at time t and the slope k, the decomposition or nutrient release constant. This model has been recently used by Palm et al. (2001) in their Organic Resource Data-base (ORD) to allow comparisons of the derived rate constants, over similar evaluation times, for different species and experiments. Root square errors were used to assess fit of the model used.

Correlation and linear regression analyses were carried out between chemical parameters of the plant materials used in litterbags and their decomposition and nutrient release rates. The amount of nutrients released by plant materials to the soil was calculated by substracting the nutrients remaining in the residues at the end of the field incubation from the total amount of nutrients initially applied. SAS (SAS Institute, 1989) was used for the statistical analysis.

Table 1. Initial chemical characteristics of the 12 plant materials evaluated.

Treatment	C	N	P	K	Ca	Mg	C/N	C/P	N/P
.	%	%	%	%	%	%	.	.	.
CAN	44.5	3.7	0.27	1.79	1.04	0.35	12.0	165.0	13.7
CRA	44.3	3.3	0.15	1.69	1.63	0.41	13.5	295.3	21.9
IND	44.8	3.9	0.19	1.72	1.77	0.43	11.6	235.9	20.4
MDEE	45.5	4.6	0.36	1.77	1.02	0.36	9.8	126.5	12.9
MPBR	45.6	4.1	0.29	1.42	1.06	0.53	11.0	157.1	14.3
MPIT	45.0	3.7	0.26	1.39	1.12	0.61	12.3	173.1	14.0
MPTL	45.1	3.8	0.26	1.52	1.24	0.44	11.9	173.5	14.6
TTH	38.8	3.9	0.25	3.47	3.49	0.74	9.9	155.1	15.7
INDm	44.5	2.9	0.16	1.56	1.37	0.40	15.3	281.7	18.4
INDs	44.0	1.5	0.11	1.33	0.76	0.36	29.7	400.2	13.5
MPITm	44.4	2.9	0.23	1.53	0.90	0.54	15.1	194.6	12.9
MPITs	43.1	1.4	0.16	1.84	0.43	0.39	30.8	269.4	8.8

Treatment	ADF	NDF	N-ADF	*HEM*	L	PP	IVDMD	L/N	PP/N	(L+PP)/N
.	%	%	%	%	%	%	%	.	.	.
CAN	33.5	44.1	0.70	10.6	6.5	8.4	69.6	1.8	2.3	4.0
CRA	42.6	64.2	1.53	21.6	17.7	4.8	46.5	5.4	1.5	6.9
IND	28.1	36.8	0.76	8.7	6.9	8.6	72.4	1.8	2.2	4.0
MDEE	24.0	46.6	0.73	22.6	6.9	9.3	70.4	1.5	2.0	3.5
MPBR	25.6	46.2	0.48	20.6	5.5	8.3	70.0	1.3	2.0	3.3
MPIT	27.8	43.1	0.43	15.3	6.1	8.9	71.5	1.7	2.4	4.1
MPTL	28.9	45.6	0.56	16.6	6.3	8.9	69.1	1.7	2.3	4.0
TTH	25.2	26.6	1.41	1.4	4.6	8.7	77.4	1.2	2.2	3.4
INDm	38.5	49.1	0.59	10.7	8.1	7.8	62.6	2.8	2.7	5.5
INDs	54.0	67.6	0.33	13.7	10.0	6.6	50.9	6.8	4.4	11.2
MPITm	35.1	49.2	0.39	14.0	7.9	8.8	63.3	2.7	3.0	5.7
MPITs	50.8	62.2	0.29	11.4	11.6	8.6	55.5	8.3	6.1	14.4

CAN=*Canavalia brasiliensis* (leaves), CRA=*Cratylia argentea* (leaves), IND=*Indigofera constricta* (leaves), MDEE=*Mucuna deerengianum* (leaves), MPIT=*Mucuna pruriens* Var. IITA-Benin (leaves), MPTL=*M. pruriens* Var. Tlaltizapan (leaves), MPBR=*M. pruriens* Var. Brunin (leaves), TTH=*Tithonia diversifolia* (leaves), INDm=*I. constricta* (stems+leaves), INDs=*I. constricta* (stems), MPITm=*M. pruriens* Var. IITA-Benin (stems+leaves), MPITs=*M. pruriens* Var. IITA-Benin (stems). C=carbon, N=nitrogen, P=phosphorus, K=potassium, Ca=calcium, Mg=magnesium. ADF=acid detergent fibre, NDF=neutral detergent fibre, N-ADF=nitrogen bound to ADF, HEM=hemicellulose, L=lignin, PP=polyphenols, IVDMD=*in vitro* dry matter digestibility.

Results

Quality of plant materials

TTH showed the lowest C, NDF, HEM and lignin contents, and the highest IVDMD, K, Ca and Mg values. Conversely, INDs and MPITs had the lowest N and N-ADF contents, but the highest C/N, PP/N and (L+PP)/N ratios (Table I). These materials, along with CRA, were also characterized by having high ADF and NDF, low IVDMD and high L/N ratio. In addition, CRA had the highest lignin content and N/P ratio, but lowest PP, IVDMD and PP/N ratio, while MDEE had the highest N, P, HEM and PP contents, and the lowest ADF value and C/P ratio (Table 1).

Decomposition and nutrient release rates

Large dry weight losses occurred in the first 2 weeks of the experiment but subsequently slowed down and remained relatively stable after week 12 (Figure 2a). A similar pattern was observed for nutrient release (Figures 2b-f), with the exception of Ca release in three of the treatments studied (Figure 2e). Significant differences ($p<0.05$) were found among treatments as shown by SED bars in Figure 2.

Using the single exponential model to fit data was possible to find that the best fits were found for K release, while the worst fit was found for decomposition, as shown by the lowest and highest root square errors, respectively (Table 2). Decomposition rates showed that weight losses were highest in TTH and IND (k_D = 0.037 and 0.034, respectively), moderate in MPBR, MPTL, CAN, MPIT, MDEE, MPITm and INDm (k_D = 0.015 -0.022), and low in CRA, MPITs and INDs (k_D = 0.005 -0.009). Faster N release rates (k_N) were found in IND, INDm and MDEE (k_N = 0.048 -0.061) and lower in MPITs, CRA and MPITm (k_N = 0.011 -0.028). Faster P release rates (k_P) were found in INDs, MDEE and MPITs (k_P = 0.044-0.063), while CRA presented the lowest rate (k_P = 0.015).

Table 2. Decomposition (k_D, d^{-1}), N (k_N, d^{-1}), p (k_P, d^{-1}), K (k_K, d^{-1}), Ca (k_{Ca}, d^{-1}) and Mg (k_{Mg}, d^{-1}) release rates and root square errors (Syx) obtained when fitting the treatment mean values of dry weight and nutrient remaining against time using the single exponential model (Wieder and Lang, 1982)

Treatment	k_D	S_{yx}	k_N	S_{yx}	k_P	S_{yx}	k_K	S_{yx}	k_{Ca}	S_{yx}	k_{Mg}	S_{yx}
CAN	0.019	18.7	0.045	15.4	0.033	15.2	0.097	2.1	0.008	4.7	0.022	11.0
CRA	0.009	16.9	0.026	18.4	0.015	18.6	0.101	3.5	nd	nd	0.013	8.5
IND	0.034	17.2	0.061	12.1	0.024	14.0	0.184	1.8	0.031	10.2	0.053	9.0
MDEE	0.019	18.3	0.048	15.7	0.044	14.3	0.116	3.2	nd	nd	0.019	10.4
MPBR	0.022	17.4	0.045	13.6	0.032	12.6	0.090	2.4	0.011	6.8	0.026	9.5
MPIT	0.020	18.9	0.039	15.5	0.029	14.7	0.099	3.4	0.012	9.7	0.028	10.8
MPTL	0.021	17.0	0.042	14.8	0.030	13.6	0.086	2.3	0.013	11.2	0.032	11.4
TTH	0.037	16.7	0.044	14.7	0.022	13.1	0.231	0.8	0.041	14.2	0.066	8.9
INDm	0.015	18.8	0.054	15.0	0.028	16.3	0.207	2.5	0.030	15.0	0.074	9.5
INDs	0.005	10.3	0.040	18.0	0.063	17.4	0.181	3.6	0.019	21.7	0.122	10.1
MPITm	0.017	18.8	0.028	18.4	0.032	17.0	0.129	2.8	0.009	7.9	0.027	11.6
MPITs	0.008	16.3	0.011	20.3	0.044	18.2	0.201	2.6	nd	nd	0.026	12.5

nd. not detennined. Treatment abbreviations are as shown in Table

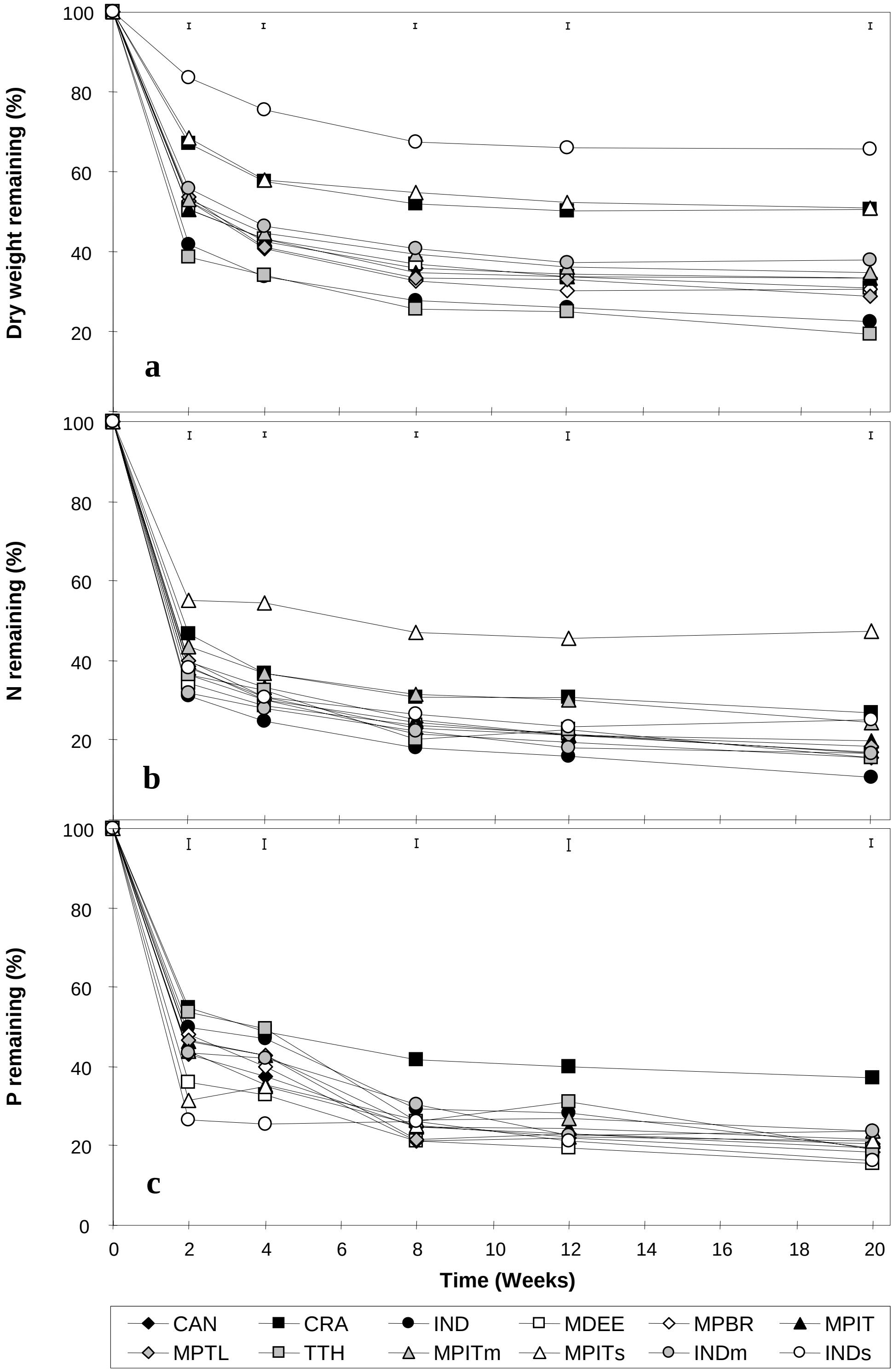

Figure 2. Dry weight loss (a), and N (b) and P (c) release patterns by 12 plant materials during 20 weeks evaluation. Vertical bars refer to standard error of the difference in means (SED) (n=4). Treatment abbreviations as shown in Table 1.

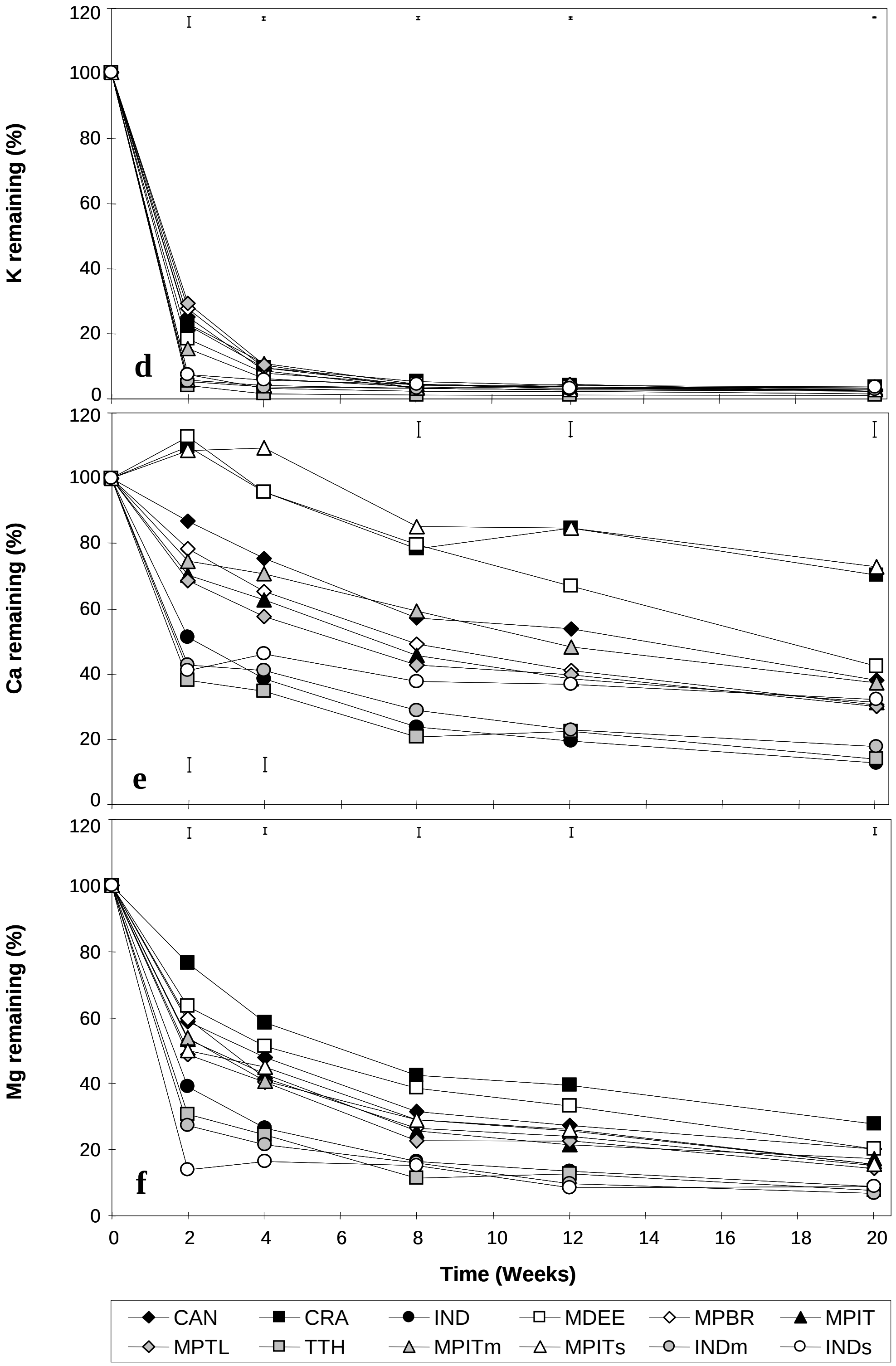

Figure 2. Contd'. K(d), Ca(e) and Mg(f) release patterns by 12 plant materials during 20 weeks evaluation. Vertical bars refer to standard error of the difference in means (SED) (n=4). Treatment abbreviations as shown in Table 1.

For K, high release rates were obtained in all treatments ($k_K \geq 0.086$). Higher K release rates were found in TTH ($k_K = 0.231$), lndigofera materials (k_K=0.181-0.207) and MPITs (k_K=0.201); while lower K release rates were found for MPTL and MPBR (k_K=0.086 and 0.090, respectively). Since CRA, MDEE and MPITs presented initial accumulation of Ca in their tissues, instead of net release, these treatments were not fitted with the model. IND, INDm and TTH, on the other hand, showed high rates of Ca release (k_{Ca}=0.030-0.041), while the rest of treatments presented relatively low rates (k_{Ca}=0.008- 0.019). The highest Mg release rate was found in INDs (k_{Mg}=0.122). IND, INDm and TTH showed intermediate rates (k_{Mg}=0.053-0.074), and CRA and MDEE showed the lowest rates (k_{Mg}=0.013 and 0.018, respectively).

Relationships between the quality of plant materials and their decomposition and nutrient release rates

A significant positive correlation ($P<0.05$) was found between decomposition rates and N, K, Ca and Mg content, and IVDMD; while a negative correlation was found for ADF, NDF, lignin and the C/N, C/P, L/N and (L+PP)/N ratios (Table 3). The quality parameters showing the stronger relationships were NDF ($r = -0.959$, $P<0.001$) and IVDMD ($r = 0.871$, $P<0.001$). These relationships could be represented by linear regressions between these quality parameters and decomposition rates (Figure 3), where $k_D=0.057-0.0008*NDF$ ($R^2=0.92$) or $k_D=-0.0381+0.0009*IVDMD$ ($R^2=0.76$).

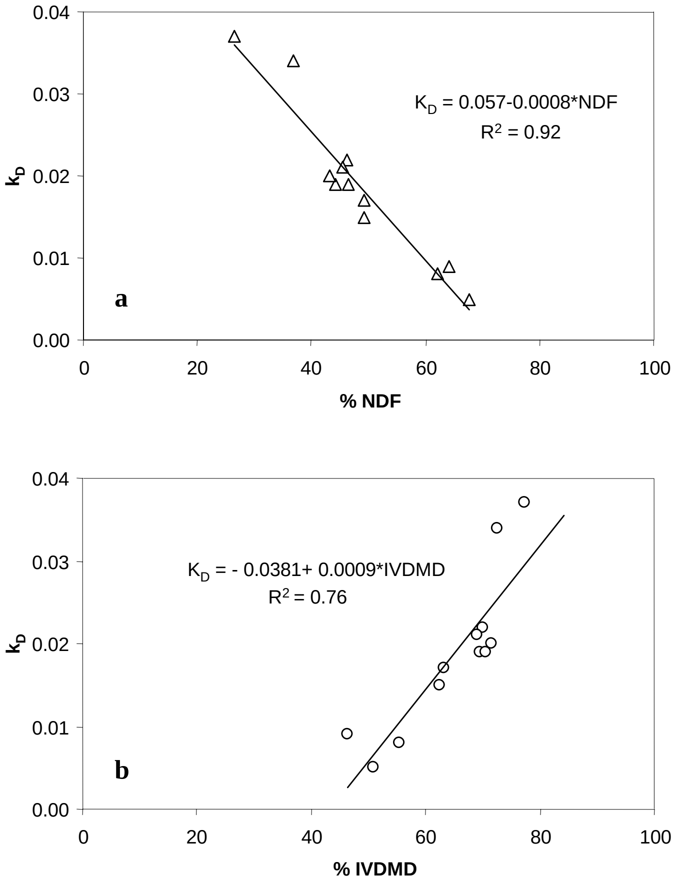

Figure 3. Linear regression between (a) neutral detergent fibre. NDF (Δ) and (b) *in vitro* dry matter digestibility, IVDMD (o) of plant materials evaluated and their respective rates of decomposition (K_D) (n=12).

Some quality parameters of plant materials were also significantly correlated to nutrient release rates (Table 3). While N content and IVDMD showed a positive correlation with N release rates, ADF, NDF and lignin contents and the C/N, L/N and (L+PP)/N ratios were negatively correlated. The best indicators of this process were the L/N and (L+PP)/N ratios and IVDMD as indicated by their greater correlation coefficients. For P release, significant correlations were found for Ca and N-ADF contents and the C/N, N/P and PP/N ratios. While K release rates were only correlated with C and HEM contents, Ca release rates correlated with C, K, Ca, N-ADF and HEM contents and the N/P ratio. Mg release rates only correlated with C/P ratios

Table 3. Pearson correlation coefficients (r) between chemical characteristics of organic materials and their decomposition (k_D), and N (k_N), P (k_P), K (k_K), Ca (k_{Ca}) and Mg (k_{Mg}) release rates

	k_D	k_N	k_P	k_K	k_{Ca}	k_{Mg}
C	-0.365	0.166	0.161	-0.678 *	-0.704 *	-0.312
N	0.695 *	0.591 *	-0.539	-0.449	0.041	-0.472
K	0.596 *	0.038	-0.326	0.535	0.698 *	0.083
Ca	0.738 **	0.355	-0.582 *	0.399	0.823 **	0.171
Mg	0.613 *	0.014	-0.438	0.163	0.330	-0.013
ADF	-0.811 **	-0.573 *	0.500	0.325	-0.090	0.413
NDF	-0.959 ***	-0.587 *	0.499	-0.108	-0.474	0.121
N-ADF	0.357	0.098	-0.654 *	0.085	0.743 *	-0.147
HEM	-0.491	-0.172	0.125	-0.753 **	-0.801 **	-0.459
L	-0.684 *	-0.584 *	-0.051	-0.024	-0.153	-0.104
IVDMD	0.871 ***	0.592 *	-0.282	-0.034	0.254	-0.166
C/N	-0.700 *	-0.574 *	0.700 *	0.412	-0.084	0.451
C/P	-0.632 *	-0.225	0.388	0.406	0.186	0.648 *
N/P	0.270	0.470	-0.663 *	0.021	0.705 *	0.081
L/N	-0.771 **	-0.706 **	0.469	0.321	-0.049	0.247
PP/N	-0.514	-0.583 *	0.662 *	0.471	-0.079	0.318
(L+PP)/N	-0.717 **	-0.697 *	0.565	0.393	-0.058	0.287

Quality parameters abbreviations are as shown in Table 1. *, **, ***=probabilities associated to pearson correlation coefficients at $p<0.05$, $p<0.01$ and $p<0.001$, respectively. Note: Number of data for analyses=12, except k_{Ca} where n=9.

Nutrient release by plant materials

Total release of nutrients, from plant materials after 20 weeks (Table 4), showed that higher amounts of N were released by MDEE, MPBR, IND and TTH (124-144 kg ha^{-1}), while MPITs and INDs showed the lowest N release (27.6 and 41.5 kg ha^{-1}, respectively). The largest amount of P was released by MDEE and MPBR (11.4 and 8.9 kg ha^{-1}, respectively), and the lowest by CRA and INDs (3.5 kg ha^{-1}). TTH, on the other hand, presented the highest release of K, Ca and Mg amounts among all treatments evaluated (129.3, 112.6 and 25.9 kg ha^{-1}, respectively); while the lowest release of these nutrients was 48.3 kg ha^{-1} K in INDs, 4.4 kg ha^{-1} Ca in MPITs and 10.6 kg ha^{-1} Mg in CAN.

Table 4. Estimated nutrient release (kg ha^{-1}) for each plant material evaluated after 20 weeks

	Total nutrient release (kg ha^{-1})				
	N	P	K	Ca	Mg
CAN	115.7	8.0	65.7	24.1	10.6
CRA	89.9	3.5	61.2	18.1	11.2
IND	129.8	5.7	63.6	57.8	14.8
MDEE	144.5	11.4	65.0	22.0	10.8
MPBR	130.9	8.9	51.9	27.7	17.0
MPIT	109.7	7.7	50.6	28.8	19.1
MPTL	115.9	7.9	55.7	32.4	14.3
TTH	124.4	7.6	129.3	112.6	25.9
INDm	91.1	4.5	57.1	42.1	14.2
INDs	41.5	3.5	48.3	19.3	12.4
MPITm	83.3	6.5	56.0	21.1	17.3
MPITs	27.6	4.7	67.2	4.4	12.5
SED	1.3	0.4	0.3	1.4	0.5

Treatment abbreviations are as shown in Table 1. SED: Standard error of the difference in means. n=4.

Discussion

Decomposition and nutrient release of plant materials generally followed an exponential trend. Differences among plant materials were related to tissue quality even among closely related species (i.e. *Mucuna*). Significant relationships were detected between the quality of plant materials and their respective decomposition and nutrient release rates (Table 3). NDF and IVDMD were the quality parameters most related to decomposition rates in this study (Table 3; Figure 3). Our results for NDF are consistent with results by Gupta and Singh (1981) showing that plant cell wall content is an important predictor of decomposition rates. On the other hand, although Tian et al. (1996) estimated the decomposability of plant residues by an 'in vivo' ruminant nylon-mesh bag assay, the use of IVDMD as an index related to decomposition in the field has not been reported elsewhere. The highly significant ($P<0.00l$) correlations obtained in this study between NDF and IVDMD, and plant decomposition suggests that lab-based NDF or IVDMD tests could be used as surrogates for decomposition of plant tissue. This finding could be of practical importance for screening of plant materials for different farm uses. Such tests can save time and reduce variability associated with decomposition studies in the field. Other indices studied which have already shown potential in the literature include N and lignin content, and the C/N, L/N and (L+PP)/N ratios because of their correlation with decomposition rates (see Mafongoya et al., 1998).

The rates of nutrient release were also related to the chemical composition of the plant materials studied as shown in Table 3. Higher correlations were found for N release and the L/N and (L+PP)/N ratios, for P release and the C/N and N/P ratios, for K release and the C and HEM contents, for Ca release and Ca and HEM content, and for Mg release and the CIP ratio. Previous studies have shown that lower N release rates from plant materials were related to high L/N ratios (Singh et al., 1999; Thomas and Asakawa, 1993) and (L+PP)/N (Barrios et al., 1997; Handayanto et al., 1994; Lehmann et al., 1995; Thomas and Asakawa, 1993; Vanlauwe et al., 1997b) for several species. P mineralization rates from decomposing plant materials have been correlated to N/P ratios (Palm and Sanchez, 1990) and L/N and C/N ratios (Singh et al., 1999) and this may be related to different decomposer communities developing on plant materials of different quality. Ca release, on the other hand, has been related to cell wall constituents (Attiwill, 1976; Luna- Orea et al., 1996) and polyphenols (Lehmann et al., 1995). Mg release, also, has been related to cell wall constituents (Luna-Orea et al., 1996) and to initial Mg content in the tissues (Lehmann et al., 1995). Nevertheless, the high potential for K leaching from plant tissues is probably responsible for the limited reports in the literature of significant relationships between plant quality indices and K release as suggested by Tian et al. (1992).

High initial nutrient contents in plant materials can be responsible for high decomposition and net nutrient release because of enhanced microbial growth and activity; however, considerable contents of structural polysaccharides like HEM and lignin, can reduce the effect of initial nutrient content because of physical protection of other cell constituents from microbial attack (Chesson, 1997; Mafongoya et al., 1998). Polyphenols in plant tissues can also reduce decomposition and nutrient release by binding of cell wall constituents and proteins (i.e. Vanlauwe et al., 1997b). The type of polyphenols and their relative content in plant tissues is also important to consider when studying N mineralization from plant materials because different polyphenols have different chemical activities. Earlier studies indicate that the method of drying of legume plant materials has an effect on type and concentration of polyphenols. It has been shown that ovendrying can reduce soluble polyphenol concentrations compared to airdrying (Mafongoya et al., 1997).

Our total polyphenol values are generally higher than those reported for other tropical plant materials as reviewed by Mafongoya et al. (1998). Higher values may be a result of methodological differences. While higher tissue: solvent ratios may not extract all polyphenols (Constantinides and Fownes, 1994) our modified extraction method using a greater proportion of methanol (70%) compared to the Anderson and Ingram (1993) standard methodology (50%), as well as the addition of formic and ascorbic acids as antioxidants may have led to higher total polyphenol values. In addition, plants growing in soils with poor N availability, as in the case of volcanic-ash soils, can result in higher concentrations of polyphenols than those growing in more fertile soils (Palm et al., 2001).

Decomposition and nutrient release trends for each treatment (Table 2; Figure 2) suggest that these processes are related. Significant correlations ($P<0.05$) were found between decomposition and N release ($r = 0.596$), K and Ca release ($r = 0.912$) and K and Mg release ($r = 0.636$) (data not shown). Significant correlations were also found by Singh et al. (1999) between dry weight loss and N release rates. Lehmann et al. (1995), on the other hand, found significant correlations among dry matter, N and Ca losses, but no connection between Mg or K with N and dry matter losses.

Although decomposition and nutrient release rates found in this study were sometimes higher than those reported by other researchers using similar methodology they fall within the range observed for tropical zones (Handayanto et al., 1994; Mafongoya et al., 1998; Mwiinga et al., 1994; Palm and Sanchez, 1990; Thomas and Asakawa, 1993; Tian et al., 1992). The high rates found in this study could be linked to the intrinsic characteristics of the materials used (species, age, quality, etc.) but also to the climatic conditions (i.e. high moisture and favourable temperature) during the first weeks of the experiment (Figure 1). It is well known that temperature and precipitation can influence the pattern and rate of decomposition of plant materials (Gupta and Singh, 1981).

Nitrogen release rates in this study were higher than those of dry weight loss (Table 2), and this is consistent with previous studies by Mwiinga et al. (1994), Palm and Sanchez (1990), Schroth et al. (1992) and Tian et al. (1992). Phosphorus release rates were usually higher than decomposition rates with the exception of TTH and IND. This could be interpreted as potential for a more gradual P release to the soil from these plant materials. Although K and Mg release rates were higher than decomposition rates, Ca release rates were lower for CRA, MDEE and MPITs as they presented initial immobilisation. Ca immobilisation has been previosuly reported by other authors (Lehmann et al., 1995; Palm and Sanchez, 1990; Schroth et al., 1992) and generally explained by the accumulation of Ca by funghi on decomposing residues.

Plant parts of the same species often show different patterns and rates of decomposition and nutrient release. In our study, plant leaves showed faster decomposition and N release rates than mixtures of leaves and stems, and these mixtures were faster than stems evaluated. In contrast, P release showed the opposite trend (Table 2). For K, Ca and Mg release, however, no consistent trends were found. These findings suggest that potential nutrient contributions by green manures would be overestimated when rates are based on leaves while their application in the field is generally as a mixture of leaves and stems. Interactions among plant parts could affect expected patterns of decomposition and nutrient release. According to Mafongoya et al. (1998), if decomposition and nutrient release patterns from a mixture of plant materials reflect the weighted averages of the individual components no interactions occurred; if this is not the case, interactions may have taken place. Interactions between stems and leaves have been reported before and explained as a result of high soluble C in the stems, which caused immobilization of N from leaf tissues (Quemada and Cabrera, 1995).

Knowledge of decomposition patterns and rates for different plant materials available on-farm is important for decision making about their optimal use. However, the total amount of nutrients contained in plant materials is critical (Palm, 1995). Results in Table 4 show that the application of dry leaf materials from all species (except CRA) at a rate of 3.75 Mg ha^{-1} can release more than 109 kg ha^{-1} of N and 5 kg ha^{-1} of P, and more than 50, 22 and 10 kg ha^{-1} of K, Ca and Mg, respectively, after 20 weeks of surface application to the soil. Provided that an annual crop like maize can extract close to 80 kg ha^{-1} of N, 18 kg ha^{-1} of P, 66 kg ha^{-1} of K and 15 kg ha^{-1} of Ca and 10 kg ha^{-1} of Mg from the soil (Palm, 1995) we could argue that these leaf materials can potentially supply a considerable proportion of nutrient demand by maize plants. Nevertheless, not all these nutrients would be available to the crop due to potential nutrient losses (denitrification, leaching, etc.), nutrient immobilization by the microbial biomass or simply by incorporation into recalcitrant soil organic matter pools (Vanlauwe et al., 1997a). Our results can be used as indicators of the potential amount and rate of nutrient supply by available options tested in order to improve the nutrient management efficiency of green manure systems in farmer fields. There is great interest in improving synchrony between nutrient release from plant materials and demand by the crop in order to minimize potential nutrient losses and increase nutrient recovery by the crop (Myers et al., 1994).

Conclusions

The chemical characteristics of plant materials used as green manures play a fundamental role in the decomposition and nutrient release processes. The judicious management of organic nutrient resources as green manures is dependent on using the right amount and quality of plant material, at the right time. Results from this study are useful to tropical hillside farmers for management of on-farm organic resources based on the potential size of the nutrient additions provided by plant materials as well as timing of nutrient additions to meet crop demand. In order to avoid false expectations about the nutrient supplying capacity of plant materials these should closely represent farmer options. The usefulness of different plant quality indices was assessed as they related to decomposition (i.e. NDF, IVDMD) or nutrient release (i.e. (L+PP)/N for N release). Their utility for screening of potential green manure germoplasm was also discussed.

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Nitrogen mineralization and crop uptake from surface-applied leaves of green manure species on a tropical volcanic-ash soil

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Abstract

Leaves of nine green manure (GM) species were surface applied to a tropical volcanic-ash soil at a rate of 100 kg N ha^{-1} in order to evaluate their N-fertilizer value in a glasshouse experiment. GM treatments were compared to urea at two rates, 50 kg N ha^{-1} (FN50) and 100 kg N ha^{-1} (FN100), and to a control with no fertilizer application (FN0). Two weeks after treatment application, upland rice seedlings were sown in order to conduct N uptake studies. Soil volumetric moisture content was maintained close to 50%. In general, soil showed an initial increase in inorganic N followed by a rapid decline with time. After 2 weeks of evaluation FN100, FN50 and leaves of *Mucuna pruriens* var. Tlaltizapan and *Indigofera constricta* presented higher values of inorganic N (157-109 mg N kg^{-1} soil); while, FN0 and leaves of *Mucuna deerengianum, Cratylia argentea* and *Calliandra calothyrsus* presented lower values (75-89 mg N kg^{-1} soil). N recovery by rice, at 20 weeks after planting, was highest for FN100 (59.9%) followed by *Canavalia brasiliensis* (54.6%), *Calliandra calothyrsus* (47.4%) and *M. pruriens* var. IITA-Benin (32.4%); while, *M. pruriens* var. Tlaltizapan, FN50, *Tithonia diversifolia* and *I. constricta* presented lower N uptake (13-20%). Significant relationships were found between some quality parameters of GM evaluated (i.e. total N, fibers, lignin and polyphenol content), soil N availability and rice N uptake. These results suggest that GM that decomposed and released N slowly resulted in high N uptake when they were used at pre-sowing in a tropical volcanic-ash soil.

Keywords: Mineralization - Nitrogen - Organic fertilizers - Plant nutrition - Plant tissue quality

Introduction

N is usually the most limiting nutrient in tropical soils and considerable efforts have been made to develop alternative or complementary cost-effective practices to N fertilization (Sánchez 1981). Green manures (GM) are considered among these alternative management practices since they can lead to increased soil N availability (Giller and Wilson 1991). A predictive knowledge of GM mineralization patterns, however, is needed for improved nutrient use efficiency in agroecosystems (Constantinides and Fownes 1994; Kass et al. 1997; Giller and Cadisch 1997). While very fast N mineralization rates can be responsible for considerable N losses through leaching, denitrification or volatilization, when N mineralization is very slow little N availability can lead to limitations in crop growth (Myers et al. 1994).

The best way to synchronize soil N availability to crop demand is by managing the quantity, quality, timing and placement of plant materials added to the soil (Palm 1995; Mafongoya et al. 1998). The chemical composition of plant materials used (or quality) is one of the most important factors that affect N mineralization rates (Swift et al. 1979; Heal et al. 1997). Plant materials poor in N have limited use in the short term (Constantinides and Fownes 1994) since low N content limits the growth of microorganisms involved in decomposition. The C/N ratio is a useful guide to predict N mineralization patterns. According to Frankenberger and Abdelmagid (1985) C/N ratios greater or equal to 19 limit N availability. Nevertheless, the detection of N mineralization in plant materials with C/N ratios >100 suggest that C compounds such as lignin (L), or polyphenols (PP) can be largely regulating this process

(Thomas and Asakawa 1993). According to Palm and Sánchez (1991), the PP content in tropical legumes can play a greater role in N mineralization than N content or the L/N ratio. This is consistent with Tian et al. (1992), who showed that plant materials with low contents of N, L and PP decomposed and mineralized N rapidly. Furthermore, Handayanto et al. (1994, 1995) and Barrios et al. (1997) also found that the (L+PP)/N ratio significantly correlated with N mineralization.

This study had the following objectives: (1) to evaluate the effect of foliage from nine GM on soil N availability in a tropical volcanic-ash soil, (2) to determine N uptake by an indicator crop (upland rice), and (3) to relate the quality of plant materials evaluated to both their N supplying capacity and the N uptake by the indicator crop.

Materials and methods

Site description

A glasshouse study was carried out at the Centro Internacional de Agricultura Tropical (CIAT) located at 3°30'N 76°21'W and 965 masl. Glasshouse mean temperature (21°C) and relative humidity (67%) were maintained constant during the whole period of study.

Description of GM species and soil

GM were selected on the basis of their adaptation to the tropical hillside environment and to volcanic-ash soils, and their differences in plant chemical composition (plant tissue quality). These species included: *Calliandra calothyrsus* Meissn. (CAL), *Canavalia brasiliensis* Mart. ex Benth. (CAN), *Cratylia argentea* Benth. (CRA), *Indigofera constricta* Rydb. (IND), *Mucuna deerengianum* (Bort.) Merr. (MDEE), *Mucuna pruriens* (Stick.) DC. var. IITA-Benin (MPIT), *M. pruriens* (Stick.) DC. var. Tlaltizapan (MPTL), *M. pruriens* (Stick.) DC. var. Brunin (MPBR) and *Tithonia diversifolia* (Hems.) Gray (TTH). Foliage of herbaceous plants (CAN and Mucunas) and TTH was harvested at flowering, while foliage of trees (CAL, CRA and IND) was harvested 6 months after the last pruning.

N concentrations in GM leaves ranged from 2.65% in CAL to 4.63% in MDEE (Table 1). CAL had the highest concentrations of C, acid detergent fiber (ADF) and PP, and highest C/N, L/N, PP/N and (L+PP)/N ratios; while TTH had the lowest contents of C, neutral detergent fiber (NDF), hemicellulose (HEM) and L, as well as the lowest C/N, L/N and (L+PP)/N ratios. IND also had low NDF and HEM contents. CRA had the highest NDF and L contents, and the lowest PP value and PP/N ratio.

The volcanic-ash soil used in the experimental pots was collected from the top 20 cm of an Oxic Dystropept (USDA 1998) located in the San Isidro farm (Pescador, Cauca, Colombia) and later passed through a 2-mm mesh. Soil characteristics included: pH (H_20) 5.1, 50 g C kg^{-1}, 3 g N kg^{-1}, 12 mg NH_4^+-N kg^{-1}, 42 mg NO_3^--N kg^{-1}, and 1.1 and 2.5 cmol kg^{-1} for Al and Ca, respectively. Soil bulk density was 0.8 g cm^{-3} and P availability was low (4.6 mg Bray-P kg^{-1}) as a result of a high allophane content (52-70 g kg^{-1}) and high P sorbing capacity (Gijsman and Sanz 1998). Triple super phosphate was added to the soil at an equivalent rate of 50 kg P_2O_5 ha^{-1} before establishing the experiment.

The experiment was a randomized complete block design with four replicates. The leaves harvested from selected GM were thoroughly mixed and air and oven dried (55±5°C). Dry plant materials were then fragmented into small pieces (<1.5 cm long) and surface applied to 1.5 kg volcanic-ash soil contained in plastic pots at a rate of 100 kg N ha^{-1}. Three additional treatments were established: urea applications of 50 and 100 kg N ha^{-1} (FN50 and FN100, respectively) and an unfertilized treatment (FN0) as a control.

Soils were capillary-wetted by placing pots on water-filled plastic saucers (Handayanto et al. 1994) so that volumetric moisture content was maintained close to 50%, while leaching was prevented. Fifteen days after plant materials were added five upland rice seeds (*Oryza sativa* L. var. Oryzica savana 10) were sown in each pot at 1 cm depth. Two weeks after germination rice plants were thinned to two plants per pot.

Table 1. Quality parameters for initial plant materials added to soil. ADF Acid detergent fiber, NDF neutral detergent fiber, HEM hemicellulose, L lignin, PP polyphenols. CAL *Calliandra calothyrsus*, CAN *Canavalia brasiliensis*, CRA *Cratylia argentea*, IND *Indigofera constricta*, MDEE *Mucuna deerengianum*, MPBR *Mucuna pruriens* var. Brunin, MPIT *Mucuna pruriens* var. IITA-Benin, MPTL *Mucuna pruriens* var. Tlaltizapan, TTH *Tithonia diversifolia*

Treatment	C	N	ADF	NDF	HEM	L	PP	C / N	L / N	PP / N	(L+PP) / N
	----------------------------			%		----------------------------					
CAL	49.4	2.65	43.7	63.2	19.4	14.50	18.44	18.6	5.47	6.96	12.43
CAN	44.5	3.71	33.5	44.1	10.6	6.52	8.42	12.0	1.76	2.27	4.03
CRA	44.3	3.28	42.6	64.2	21.6	17.72	4.78	13.5	5.40	1.46	6.86
IND	44.8	3.87	28.1	36.8	8.7	6.88	8.59	11.6	1.78	2.22	4.00
MDEE	45.5	4.63	24.0	46.6	22.6	6.86	9.28	9.8	1.48	2.00	3.49
MPBR	45.6	4.14	25.6	46.2	20.6	5.54	8.28	11.0	1.34	2.00	3.34
MPIT	45.0	3.65	27.8	43.1	15.3	6.10	8.92	12.3	1.67	2.44	4.12
MPTL	45.1	3.79	28.9	45.6	16.6	6.26	8.89	11.9	1.65	2.35	4.00
TTH	38.8	3.93	25.2	26.6	1.4	4.56	8.65	9.9	1.16	2.20	3.36

Sampling and chemical analyses

All treatments were evaluated at 2, 4, 8, 12 and 20 weeks after initiating the experiment by carefully removing the remaining decomposing material and sampling the whole soil from the pots. Two samples (20 g) were taken for moisture determination (105°C until constant weight) and the extraction of inorganic N. Soil inorganic N was extracted by shaking the 20 g of soil in 100 ml of 2 M KCl on an end-to-end shaker at 150 r.p.m. for 1 h, and filtering through Whatman no.1 filter paper, previously washed with deionized water and 2 M KCl. The resulting soil extracts were then analyzed colorimetrically with an autoanalyzer (Skalar Sun Plus) to determine NH_4^+-N and NO_3^--N contents, and expressed on a dry soil basis (CIAT 1993).

At 20 weeks, the fresh weight of aboveground biomass (leaves+stems and panicles) and roots was determined and they were later air and oven dried (55±5°C) for dry weight determination and chemical analysis. Subsamples of each plant material evaluated were analyzed chemically for C, N, ADF, NDF, HEM, L and PP content. In addition, rice plant components sampled at 20 weeks (leaves+stems, panicles and roots) were analyzed for their N content. Dry plant tissues were ground and sieved (1 mm) before analysis. C and N were determined by colorimetry using an autoanalyzer (Skalar Sun Plus). ADF, NDF and L were determined using modified techniques of Van Soest and Vine (Harris 1970) and PP with a modified Anderson and Ingram (1993) method that uses 70% methanol, 0.5% formic acid and 0.05% ascorbic acid as extractant (Telek 1989), the Folin-Ciocalteu reagent and tannic acid as standard. Hemicellulose was calculated by the difference between NDF and ADF.

Calculations and statistical analysis

Plant N uptake (milligrams) was calculated by multiplying tissue N contents by tissue dry weights. In order to assess N use efficiency as a function of GM and fertilizer treatments, plant N uptake was expressed as a percent of initial N applied (N recovery) using the following calculation:

$$\text{N recovery (\%)} = \frac{\text{Plant N uptake in treatment} - \text{Plant N uptake in control}}{\textit{Initial N added}} \times 100$$

All variables evaluated in soil and rice were subjected to ANOVA. Whenever necessary, variables were root square-transformed to normalize data and homogenize variance. SEs of the difference in means (SED) were calculated from the ANOVA and reported with the data. Correlation analyses were conducted to assess the relationships between quality parameters of GM and soil available N and rice N uptake. SAS (SAS Institute 1989) was used for all statistical analysis.

Results and discussion

Soil N availability

Although fertilized controls (FN100 and FN50) generally produced the highest values of soil available N, considerable quantities of inorganic N were also recovered from soil, after GM application (Fig. 1), suggesting the potential of these plant materials as biofertilizers, as discussed by Palm (1995), Kass et al. (1997), Mafongoya et al. (1998) and Aulakh et al. (2000). GM, however, differed in their impact on soil N availability. Plant materials like MPTL and IND showed high initial soil inorganic N, while MDEE, CRA and CAL had a reduced initial impact on soil N availability, presumably as a result of their higher rates of decomposition and N release (Table 2). A "priming effect" on soil organic matter (SOM) mineralization, as a result of N additions (as mineral or organic fertilizers), could also be occurring (Lovell and Hatch 1998). Nevertheless, SOM mineralization in volcanic-ash soils is lower than expected due to the protection of SOM particles in these soils (Gijsman and Sanz 1998).

Table 2. Estimated decomposition and N release rates (d^{-1}) for initial plant materials added to soil. Data for rate calculations obtained from a 20 weeks litterbag field experiment conducted in Pescador (Cauca). A single exponential model was used to fit the data. (Cobo et al., 2002). ND Not determined; for other abbreviations see Table 1.

Treatment	Decomposition rate	N release rate
CAL	ND	ND
CAN	0.019	0.045
CRA	0.009	0.026
IND	0.034	0.061
MDEE	0.019	0.048
MPBR	0.022	0.045
MPIT	0.020	0.039
MPTL	0.021	0.042
TTH	0.037	0.044

Soil NH_4^+ levels significantly increased ($P<0.01$) at week 2, especially in FN100 (111.5 mg N kg^{-1} soil) and FN50 (81 mg N kg^{-1} soil), and diminished to almost zero by week 12. Among GM treatments, IND showed the highest value of soil NH_4^+ (76.2 mg N kg^{-1} soil) and CAL the lowest (47.7 mg N kg^{-1} soil). Conversely, soil NO_3^- values after 2 weeks were lower than starting values (i.e. 42 mg N kg^{-1} soil), except for FN100, but subsequently, at week 4, there was an overall increase in soil NO_3^-, especially in TTH (87.5 mg N kg^{-1} soil), so that by week 8 soil NO_3^- values had surpassed those of NH_4^+. Following this peak, soil NO_3^- values also decreased to values close to zero.

Total inorganic N [$(NH_4^+ + NO_3^-)$-N)] increased in all treatments during the first 2 weeks of the experiment (Fig. 1). This effect was significantly higher ($P<0.01$) in FN100 (157.1 mg N kg^{-1} soil) and FN50 (116 mg N kg^{-1} soil), while in FN0 we found the lowest value (75 mg N kg^{-1} soil). Soil inorganic N then followed a declining trend with some treatments showing slightly lower values than FN0 during certain periods (i.e. CAL, CRA and IND at week 4, and MDEE at 8 weeks). This reduction of inorganic N after 4 weeks probably could be the result of rice N uptake and soil N losses, as discussed by Aulakh et al. (2000). Potential soil N losses could be mainly attributed to denitrification since free drainage was prevented by the irrigation system used, and N volatilization is expected to be low in acid soils

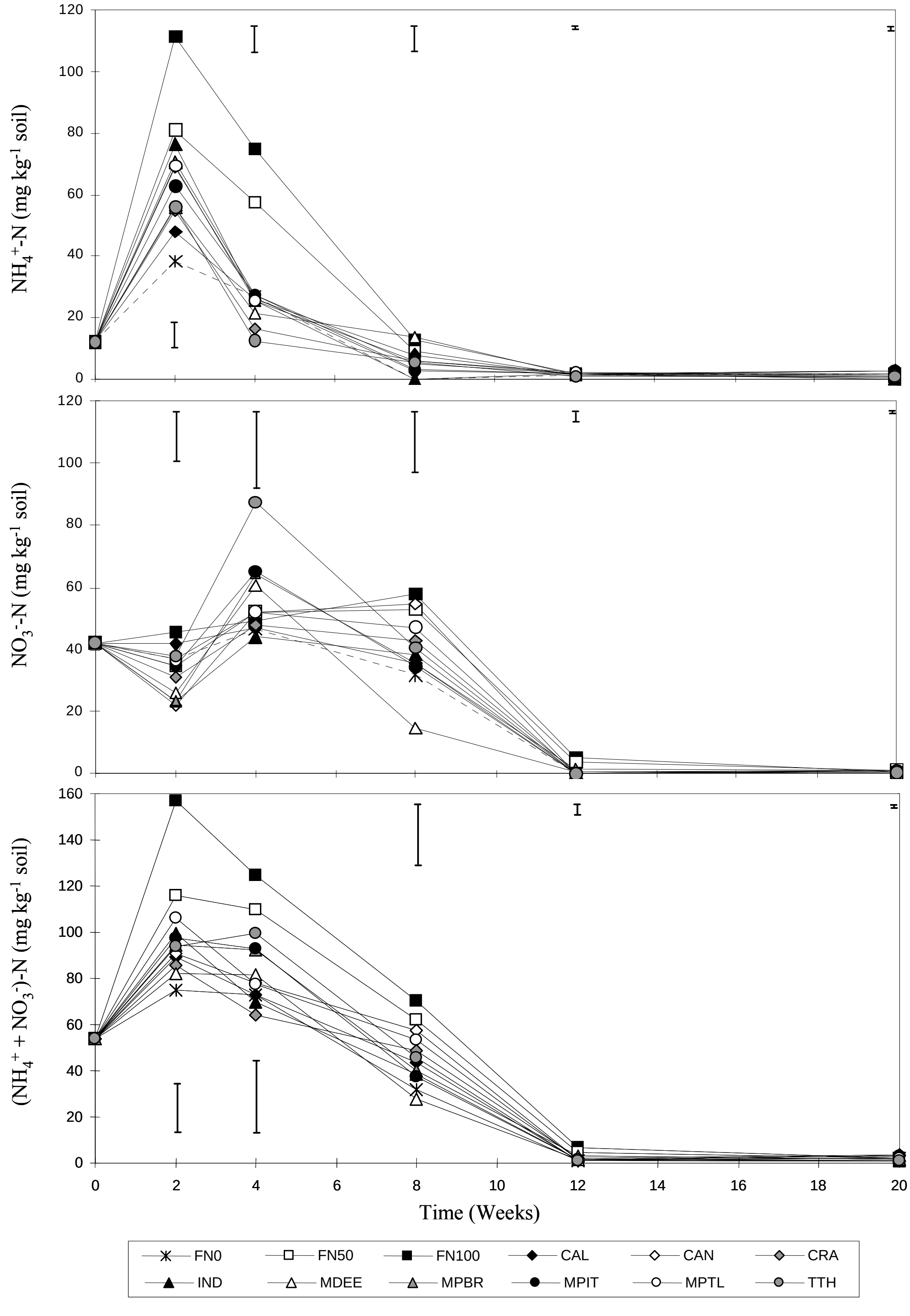

Fig. 1. Soil NH_4^+, soil NO_3^- and total soil inorganic N during 20 weeks of evaluation. Data are the mean of four repetitions. Vertical bars indicate SE of the difference in means (SED). FN0 Control with no fertilizer application, FN50 urea application 50 kg N ha^{-1}, FN100 urea application 100 kg N ha^{-1}, CAL *Calliandra calothyrsus*, CAN *Canavalia brasiliensis*, CRA *Cratylia argentea*, IND *Indigofera constricta*, MDEE *Mucuna deerengianum*, MPBR *Mucuna pruriens* var. Brunin, MPIT *Mucuna pruriens* var. IITA-Benin, MPTL *Mucuna pruriens* var. Tlaltizapan, TTH *Tithonia diversifolia*

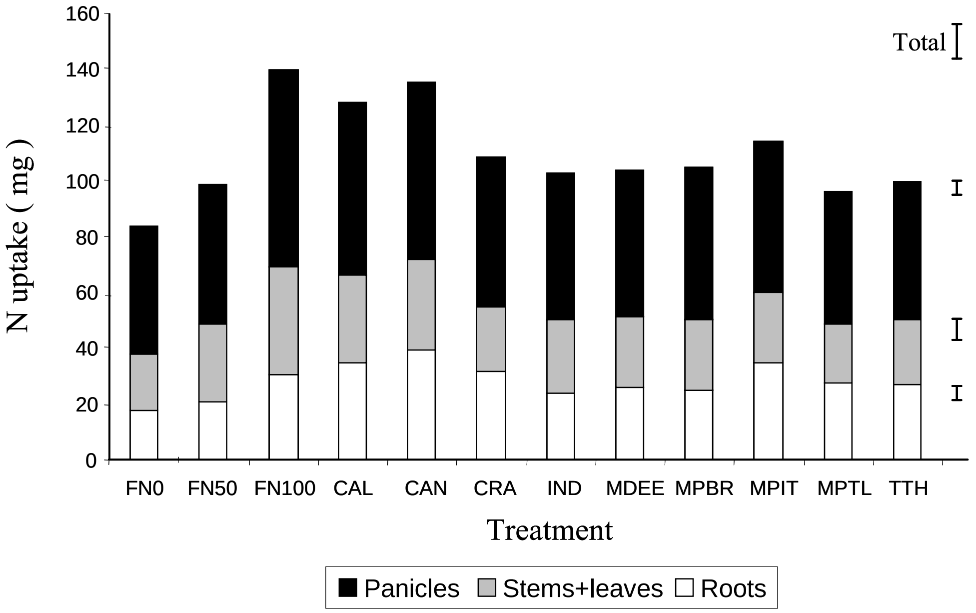

Fig. 2. Rice N uptake at 20 weeks as affected by green manure and fertilizer treatments. Data are the mean of four repetitions. Vertical bars indicate SED for each plant component. For abbreviations, see Fig. 1

(Fassbender and Bornemiza 1987). Denitrification may have occurred at microsites because of experimental soil moisture content (50%). On the other hand, the observation that some treatments had lower inorganic N values than FN0 at certain sampling dates suggests N immobilization by soil microorganisms. However, these events were transient and probably due to chemical changes of plant materials to critical levels over time (i.e. higher C/N and L/N ratios).

Rice N uptake

At 20 weeks, plants in FN100, CAL, CAN, MPIT and CRA showed significantly ($P<0.01$) higher N content than FN0 (83 mg) (Fig. 2). N uptake by rice was highest in FN100 (140 mg), but it was not significantly different from that in CAL (128 mg), CAN (135 mg) and MPIT (114 mg). This observation indicates that these GM could have considerable potential as a source of N to crops in tropical volcanic-ash soils. N uptake in the other treatments was statistically similar to N uptake in FN50 (98 mg).

A more detailed analysis showed significantly higher ($P<0.05$) leaves+stems and panicle N content in FN100, CAL and CAN than rice plants in FN0. FN100, CAL, CAN, MPIT and CRA also showed significantly higher ($P<0.05$) root N content than the control. A similar trend was found for plant dry weight. Both plant weight and N uptake were strongly correlated (data not shown).

Expressing N uptake as a percent of initial N applied we observed that N recovery by rice plants ranged from 13.1% in MPTL up to about 60% in FN100. N recovery in IND was 20.1% while in CAL it was 47.4%. Plants in FN50 only recovered 15.6% of the N initially applied (Table 3). Likewise, Fox et al. (1990) report a range of 11.2% (*Cassia rotundifolia*) to 85.1% (Fertilized control) for N recovery by sorghum receiving different legume residues. Aulakh et al. (2000), in a field study using *Vigna unguiculata* and *Sesbania aculeata* as GM, reported N recoveries of 60-79% by rice, but 11-16% by wheat. Additionally, our values for *C. calothyrsus* (47.4%) were higher than those reported by Handayanto et al. (1995) in maize which ranged between 4.2% and 23.1%. The differences in N recovery values among studies are probably due to differences in the methodology used (i.e. soil and climate conditions, indicator crop, GM type, form and rate of application, N recovery procedures and evaluation period).

Table 3. N recovery by rice from different green manures (GM) and fertilizer treatments after 20 weeks of evaluation. Data are the means of four repetitions. SED SE of the difference in means, FN50 urea application 50 kg N ha-1, FN100 urea application 100 kg N ha-1; for other abbreviations see Table 1

	Treatment										
N Recovery	FN50	FN100	CAL	CAN	CRA	IND	MDEE	MPBR	MPIT	MPTL	TTH
(%)	15.6	59.9	47.4	54.6	26.0	20.1	21.4	22.6	32.4	13.1	17.0
SED	13.4										

Relationships among plant tissue quality, soil N availability, and rice N uptake

Significant relationships were found between plant quality parameters, soil N availability and rice N uptake (Table 4). Fiber and L content, and C/N, L/N and (L+PP)/N ratios showed a negative relationship with soil NH_4^+-N and total inorganic N [$(NH_4^+ + NO_3^-)$-N)] at 2 and 8 weeks respectively. On the other hand, N and ADF content, and C/N, PP/N and (L+PP)/N ratios correlated to rice N uptake at 20 weeks (Table 4). These results are in agreement with those found by Palm and Sánchez (1991) who observed that 1 and 8 weeks after application of legume leaves to soil, soil inorganic N was significantly correlated with the PP content and the PP/N ratio of the plant material, while the L/N ratio only correlated with soil inorganic N at week 8. On the other hand, Constantinides and Fownes (1994) suggested a significant relationship between N, L, PP, L/N, PP/N, (L+PP)/N and N mineralization from a 16-week incubation experiment using legume and non-legume leaves. Handayanto et al. (1995) also found a significant correlation between N mineralization rates of *C. calothyrsus* and *Gliricidia sepium* plant materials with their contents of N, PP, their polyphenol protein binding capacity, and the C/N, PP/N, L/N and (L+PP)/N ratios.

Data for soil N availability, N uptake and GM quality, and relationships found suggest that fast-decomposing, high-quality plant materials (e.g. IND) generated high short-term soil N availability but low rice N uptake; while slow-decomposing, lower quality plant materials (e.g. CAL) had a longer-term impact, which resulted in greater N uptake by rice. Reduced performance of higher quality materials could be attributed to the limited synchrony between N mineralization from GM applied and crop uptake. This may be partly explained by the limited effective root system of rice plants before 4 weeks (Fernández et al. 1985), thus missing part of the observed flush of inorganic N at 2 weeks. Therefore, N losses would be expected in treatments generating short-term soil N availability. Pre-sowing surface application of low-quality plant materials (e.g. CAL) and/or surface application of high-quality plant materials (e.g. IND) during periods of high crop N demand (i.e. flowering) could be seen as alternatives for resource poor farmers cropping tropical volcanic ash soils. These practices would increase the agroecosystem nutrient use efficiency and synchrony by reducing potential nutrient losses and increasing N recovery by the crop.

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Table 4. Pearson correlation coefficients and associated probabilities (in parenthesis), according to linear correlation analysis between quality parameters of GM materials added to soil, soil N availability and rice N uptake (n=36). NS Not significant; for other abbreviations see Table 1

Quality parameters of GM materials	Soil N availability		Rice N uptake
	NH_4^+-N [a]	$(NH_4^+ + NO_3^-)$-N [b]	
N	NS	NS	-0.336 (0.045)
ADF	-0.355 (0.033)	-0.354 (0.034)	0.352 (0.035)
NDF	-0.335 (0.046)	-0.342 (0.041)	NS
L	-0.417 (0.011)	-0.372 (0.026)	NS
C/N	-0.341 (0.042)	NS	0.366 (0.028)
L/N	-0.447 (0.006)	-0.344 (0.040)	NS
PP/N	- 0.363 (0.029)	NS	0.323 (0.050)
(L+PP)/N	-0.462 (0.005)	NS	0.320 (0.050)

[a] NH_4^+-N extracted from soil after 2 weeks of evaluation
[b] Inorganic N $[(NH_4^+ + NO_3^-)$-N)] extracted from soil after 8 weeks of evaluation

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Plant growth, mycorrhizal association, nutrient uptake and phosphorus dynamics in a volcanic-ash soil in Colombia as affected by the establishment of *Tithonia diversifolia*

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Abstract

Tithonia diversifolia has the ability to sequester nutrients from soil in its tissues, including P, and has been shown to be useful for cycling nutrients via biomass transfer and improved fallow. We investigated the effects of its establishment from bare root seedlings (plantlets) and vegetative stem cuttings (stakes) on shoot and root growth characteristics, arbuscular-mycorrhizae (AM) associations, nutrient acquisition and utilisation, and P dynamics in a fine-textured volcanic-ash soil (Oxic Dystropept) of a mid-altitude hillside in southwestern Colombia. One year after establishment, the following determinations were made: leaf area index; shoot and root N, P, K, Ca and Mg acquisition; AM root infection; AM fungal spores per 100 g soil; soil chemical characteristics; and P fractionation into inorganic (P_i) and organic (P_o) pools. AM root infection in both coarse and fine roots was significantly greater in plants established from plantlets than those established from stakes with differences of 21 and 31 %, respectively. Nutrient uptake efficiency (µg of shoot nutrient uptake per m of root length) and use efficiency (g of shoot biomass produced per g of shoot nutrient uptake) for N, P, K, Ca and Mg were also greater with plants established from plantlets than those established from stakes.(is it right). Improved nutrient acquisition could be attributed to relief from P stress and possibly uptake of some essential micronutrients resulting from AM association. High soil variability masked the effect of the establishment method on phosphorus pools, and neither the biologically available P (H_2O-P_o, resin-P_i, and $NaHCO_3$-P_i and -P_o) nor the moderately resistant P (NaOH-extractable P) was significantly affected, although plantlets had higher values. This study has shown that on this soil when *Tithonia* is to be used as a fallow species, the use of plantlets as compared to the stake method of establishment is better for nutrient acquisition and recycling.

Keywords: Mycorrhizae, nutrient uptake, plant growth attributes, phosphorus dynamics, *Tithonia*, volcanic ash soil

Introduction

In recent years, soil fertility has declined in large areas of the Colombian Andes due to intensive land use. Long-term fallows (6-12 years), needed for soil fertility replenishment, have also virtually disappeared due to increasing population and competing land-use demands. As land use pressures mount, there is a progressive shortening of the fallow period. Hence, the development of technologies that could enhance and accelerate fallow functions and provide a similar level of ecological benefits over a shorter time compared to the natural fallow are urgently needed (Phiri et al., 2001). Such technologies are most likely to be accomplished through the introduction of improved fallow species with fast growing, superior soil conserving and fertility-regenerating properties, and with the ability to control weeds. A useful fallow species must have the ability to sequester nutrients, including P, from soils that have high inherent P reserves but low P availability. *Tithonia* (*Tithonia diversifolia* (Hemsfey) A. Gray) is one such species that has been shown to be useful for cycling nutrients via biomass transfer (Nziguheba et al., 1998).

Tithonia is a robust succulent non-N_2-fixing perennial shrub of the family Asteraceae (compositae), which grows 1 to 3 m in height and bears several bright yellow flowers similar to those of the well-known sunflower plant (*Helianthus annuus),* but the flowers are smaller (about 3 cm in diameter).

Tithonia is a native component of natural vegetation in the tropics and subtropics. It grows as a subclimax species that naturally occurs with disturbed soil conditions. *Tithonia* originated from Mexico, but is now widely distributed throughout the humid and sub-humid tropics in Central and South America, Asia and Africa (Sonke, 1997). It frequently grows wild in hedges, along roadsides, on wastelands and riverbanks, and is common in indigenous fallow systems in Southeast Asia (Jama et al., 2000). It produces large quantities of leaf biomass, and its hedges rapidly grow back after cutting and tolerate repeated pruning. Recently, there has been increasing awareness of the use of *Tithonia diversifolia* as an indigenous fallow species to improve soil fertility (Niang et al., 1996). Evidence indicates that this species has an ability to accumulate labile soil nutrients, which might otherwise be lost to runoff and leaching, and store them in its rapidly accumulating shoot biomass, which can then be used as a source of plant nutrients or biofertilizers (Nagarajah and Nizar, 1982; Gachengo, 1996; Niang et al., 1996; Jiri and Waddington, 1998; Phiri et al., 2001).

Research done by institutions such as Kenya Agricultural Research Institute (KARI), Tropical Soil Biology and Fertility Programme (TSBF) and International Centre for Research in Agroforestry (ICRAF) in the highlands of western Kenya has dramatically raised awareness and expectations of *Tithonia* green biomass for soil fertility replenishment (Niang et al., 1996). There is also growing interest in the apparent ability of *T. diversifolia*, probably in association with arbuscular-mycorrhizae (AM), to mobilize and accumulate soil P. Release of P from Tithonia green biomass is rapid, and Tithonia supplies plant available P at least as effectively as an equivalent amount of P from soluble fertilizer (Nziguheba et al., 1998).

Tithonia green biomass (green tender stems + green leaves),is relatively high in nutrients when compared to green biomass of other shrubs and trees (Jama et al., 2000). Nagarajah and Nizar (1982) reported nutrient concentration of Tithonia biomass in the ranges of 3.2 to 5.5 % N, 0.2 to 0.5 % P and 2.3 to 5.5 % K based on the analysis of 100 dry samples of green biomass in Sri Lanka. The mean values of nutrient concentration of green leaves of *Tithonia* collected in East Africa are 3.5 % N, 0.37 % P and 4.1 % K on a dry-weight basis (Jama et al., 2000). The concentration of N in *Tithonia* green biomass is comparable to that found in N_2-fixing leguminous shrubs and trees, whereas the P and K concentrations are higher than those typically found in shrubs and trees (Jama et al., 2000; Phiri et al., 2001). *Tithonia* biomass is also high in nutrients other than N, P and K. Gachengo et al. (1999), for example, found 1.8 % Ca and 0.4 % Mg per unit dry weight of the green Tithonia biomass.

Tithonia diversifolia is deliberately being introduced into mid-altitude hillside agriculture system in Colombia to enhance soil fertility (in a chemical, physical and/or biological sense) and to some extent to suppress weeds (Phiri et al., 2001). Compared with natural fallow, *Tithonia* markedly improved the availability of several essential nutrients, particularly P and K (Phiri et al., 2001). Jama et al. (2000) reported that the biomass production of *Tithonia* is influenced by establishment methods, frequency of cuttings, stand density and site conditions. To facilitate rapid establishment of *Tithonia* on a large scale, there is a need to investigate the effect of its establishment method on soil properties and plant growth attributes. *Tithonia* propagates from seeds that frequently germinate naturally under its canopy. Seedlings can be dug up and transplanted elsewhere. However, when Tithonia is established from seeds in the field, germination can be poor, especially if the seeds are sown deep or covered with a clayey soil (Jama et al., 2000). Under field conditions, Tithonia is more easily established from stem cuttings than from seeds (King'ara, 1998). The main objective of the present study was to determine the effect of method of establishment (vegetative stem cuttings versus bare-root seedlings—here called plantlets) of *Tithonia diversifolia* on shoot and root growth characteristics, AM association, nutrient acquisition and utilization, and P dynamics in soil.

Materials and methods

Site description and experimental design

This study was carried out at CIAT's "San Isidro" experimental farm in Pescador located in the Andean hillsides of the Cauca Department of southwestern Colombia (2º 48′ N, 76º 33′ W) at 1505 m.a.s.l. The area has a mean temperature of 19.3 °C and a mean annual rainfall of 1900 mm (bimodal).

The plots had a slope of approximately 30 %. The soils, derived from volcanic ashes, have been classified as Oxic Dystropepts (Soil Survey Staff, 1998), having the following characteristics: pH (H_2O) 5.1; 50 mg g^{-1} C; 3 mg g^{-1} N; 4.6 mg kg^{-1} soil of Bray-P; and 1.1 and 2.5 cmol kg^{-1} soil for Al and Ca, respectively (Cobo et al., 2000). The soil has a medium to fine texture (45 % sand, 27 % silt and 38 % clay) (IGAC, 1979) of high fragility and low cohesion with shallow humic layers. Low soil P availability is presumably the result of high allophane content (52-70 g kg^{-1}), which increases its P sorbing capacity (Gijsman and Sanz, 1998).

The two treatments used were one-year-old *Tithonia diversifolia* (Hems.) Gray (1) bare root seedlings (plantlets) and (2) vegetative stem cuttings (stakes). *Tithonia* stakes, 20-40 cm long with 4 or 5 nodes, were cut from mature plants, planted at a slanting angle of 45-60 degrees with 1 or 2 nodes below the ground level to leave 2 or more nodes above the ground. The two propagating materials were planted at the same plant density (40 000 plants/ha at a staggered spacing of 50 cm x 50 cm) in 20 x 20 m plots. Three one cubic meter monoliths, each including one *Tithonia* plant, were randomly collected within each treatment plot. The experiment was laid down as a randomized complete block (RCB) design with establishment method as treatment.

Sampling and measurements of plant growth attributes

After one year of plant growth, a sample area of 1 m^2 was randomly selected within each plot and all the above ground biomass in this area was harvested. The biomass from the rest of the plot was harvested for the total biomass determination. The biomass from the sample area was separated into leaves, stems and the reproductive structures (flowers and seeds). The leaves were used for determination of leaf area index, and the leaves, stems and reproductive structures were analysed for N, P, K, Ca and Mg. An area of 0.5 x 0.5 m was selected within the sampling area, and all the soil from the 0-5, 5-10, 10-20, 20-40, 40-60 cm soil depths was collected for root and AM determinations. These samples were air-dried and visible plant roots were removed and then gently crushed to pass through a 2-mm sieve. The <2-mm fraction was used for subsequent chemical analysis.

The leaf area (cm^2) was determined by measuring fresh leaves with an LI 3000 Area Meter (LI-Cor Inc., Lincoln, NE). The leaf area index (LAI, m^2 of leaf area per m^2 of ground area) and the specific leaf area (SLA, m^2 of leaf area per kg of dried leaves) were calculated. Measurements of photosynthetic efficiency of intact leaves were made with a portable Plant Efficiency Analyzer (Hansatech, King's Lynn, UK). Leaves were dark adapted for 20 min using leaf clips before a 5-s light pulse (1500 μmol m^{-2} s^{-1}) was supplied by an array of red light-emitting diodes The rapid turn-on of the light-emitting diodes allowed the accurate determination of Fo (minimal fluorescence intensity with all photosystem II reaction centers open while the photosynthetic membrane is in the non-energized state in the dark) and, hence, Fv (maximum variable fluorescence in the state when all non-photochemical processes are at a minimum, i.e., Fm-Fo) (Kooten and Snel, 1990; Sundby et al., 1993). The ratio of variable to maximal fluorescence (Fv/Fm = (Fm-Fo)/Fm) (Fm = fluorescence intensity with all photosystem II reaction centers closed) is a measure of the maximal photochemical efficiency of photosystem II.

Root distribution was determined using soil coring method (Rao, 1998). For each replication, a total of 12 soil cores at different soil depths (0-10; 10-20; 20-40; and 40-80 cm) were collected 10 cm from the base of the plant across the row. After washing out the roots on a 1 mm sieve, the "live" roots were hand separated from organic material. Root length was measured with the Comair Root Length Scanner (Commonwealth Aircraft Corporation, Melbourne, Australia) and expressed in km of root length per m^2 of ground area. Root biomass was determined after drying the samples in an oven at 70 °C for 2 days. The specific root length was calculated in m of root length per g of dried roots. A number of other plant attributes were determined including nutrient status of plant parts, shoot nutrient uptake, nutrient uptake efficiency (μg of uptake in shoot biomass per m of root length), and nutrient use efficiency (g of shoot biomass production per g of total nutrient uptake) (Salinas and Saif, 1990; Rao et al., 1997).

AM determinations

Mycorrhizal association was assessed by the number of spores per 100 g soil and AM root infection percentage in coarse and fine roots according to the method of Sieverding (1991). To separate spores from the soil, a 50 g sample of well-mixed soil, was suspended in water for 1 min (for sedimentation of coarse sand), and then the suspension was decanted over a series of soil sieves (a sieve with 0.350$^-$over one with 0.125$^-$ over one with 0.045-mm mesh size). Suspending and decanting were repeated three times. Root material in the top sieve was carefully washed with water and then transferred with a little water to a petri dish. The contents of the medium sieve and of the finest sieve were separately transferred to 100-ml centrifuge tubes. In the tubes, the sievings were brought into suspension in 30 ml water and 30-40 ml of a sugar solution (70 g sugar dissolved in 100 ml water) was injected into the bottom of the tube with the aid of a 50-ml syringe so that a gradient was established in the centrifuge tube. The sample was centrifuged (with a centrifuge with swinging bucket and horizontal head) at 1000 revolutions per min. for 10 min. During this process soil particles settle on the bottom and spores remain on the surface of the sugar gradient. Spores were extracted with syringe from the gradient and placed in a clean sieve with 0.045-mm mesh opening; then the spores were washed with water for 2-3 min. before being transferred in water to a petri dish. Spores in the root fraction and the centrifuged samples were observed and counted under a stereomicroscope at 40x magnification.

To determine AM fungal root infection, the soil was immersed in a tub of water and gently agitated to separate the roots from the soil. The roots were separated into coarse (> 2mm diameter) and fine roots. The roots were then washed with water using a hose over a 1-2 mm screen (to catch roots). The roots were then transferred to a flask and heated in 5% KOH at 90 °C for 15 min. The KOH was then rinsed off the roots with water on a fine sieve. Roots were stained in acidic glycerol/trypan blue for 15 min at 90 ºC and then destained and stored in 50 % acidic glycerol and subsequently used for determination of AM root infection using the modified grid intersect method (Newman, 1966).

Phosphorus fractionation and analysis

A 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. The following fractions were included: (1) resin P_i extracted with anion exchange resin membranes (used in bicarbonate form) was used to extract freely exchangeable P_i. The remaining P_o in the extraction from of the resin extraction step (H_2O-P_o) 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 and Walker, 1969) and associated with humic compounds (Bowman and Cole, 1978). (4) HCl P_i was obtained by extraction with 1.0 *M* HCl; (5) HCl hc-P and -P_o were extracted with hot and concentrated HCl; and (6) residual P was obtained by digestion 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 and Riley, 1962). All laboratory analyses were conducted in duplicate and all the data are expressed on an oven-dry weight basis.

Statistical analysis and data presentation

Analyses of variances were conducted (SAS/STAT, 1990) to determine the significance of the effects of method of *Tithonia* establishment on soil properties and plant growth attributes. 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

AM association

Establishment of *Tithonia* by plantlets resulted in significantly greater mycorrhizal root infection (P=0.05) in both coarse and fine roots, as compaewd to Tithonia established by stakes and the differences were of 21 and 31%, respectively (Table 1). The corresponding difference in the number of spores per 100 g of soil was 30% but the difference between the two methods was not statistically significant (P=0.05). The higher AM infection of plants established with plantlets could have contributed to the greater acquisition of nutrients (Table 2) observed under this treatment. Increased mycorrhizal uptake of simple forms of organic P (P_o) (Jayachandran et al., 1992) and increased net release of P from organic matter due to uptake by mycorrhizal hyphae (Joner and Jakobsen, 1994) have been demonstrated. Although the source of soil P is envisaged to be the soil solution and to be the same for both roots and hyphae, the transfer across the symbiotic interface results in increased nutrient acquisition by the plant (Smith and Read, 1997). This is because mycorrhizal hyphae, due to their small size and spatial distribution compared to roots, are able to penetrate soil pores inaccessible to roots resulting in exploitation of a larger soil volume for nutrient acquisition, particularly of non-mobile nutrients such as P, Zn and Cu (Smith and Read, 1997). Rhodes and Gerdemann (1975) demonstrated the ability of the hyphae of mycorrhizal fungi to absorb ^{32}P from a distance as much as 7 cm away from the roots. The kinetics of P uptake into hyphae may differ from that of roots. The fungal membrane transport system seems to have a higher affinity for phosphorus (lower K_m value) than roots (Cress et al., 1979), leading to more effective absorption from low concentrations in the soil solution and possibly lower threshold values below which uptake ceases (Smith and Read, 1997).

Table 1. Effect of method of establishment (stake or plantlet) on mycorrhizal (AM) association and nutrient uptake efficiency of *Tithonia diversifolia*. LSD values are at 0.05 probability level (n = 3).

Plant attributes		Method of establishment		
		Stake	Plantlet	$LSD_{(P=0.05)}$
AM infection in fine roots	(%)	49	79	11
AM infection in coarse roots	″	48	69	12
Number of spores in 100 g of soil		418	509	ns
P uptake efficiency	(µg/m)	30	48	12
N uptake efficiency	″	167	331	128
K uptake efficiency	″	379	662	130
Ca uptake efficiency	″	116	184	56
Mg uptake efficiency	″	37	61	19

ns = not significant.

The work with cassava by Yost and Fox (1979) illustrates this point. This species appears to have a very high P requirement, coupled with a very inefficient P uptake system in the absence of mycorrhizal colonization. Despite this, cassava is well known for its growth on soils of low fertility and its efficiency of uptake is markedly increased when roots are colonized by mycorrhizal fungi (Smith and Read, 1997). The increased efficiency of the plantlet to associate with mycorrhizae may be related to the initial physiological competence of the plantlet compared to the vegetative stem cutting (stake). Plantlets have all the basic components of a mature plant and are able to start photosynthesis shortly after transplanting.

Plantlets are also likely to associate with AM faster than cuttings because they already have roots and produce photoassimilates that are an essential component for an effective plant-mycorrhizal symbiosis. This symbiosis is likely to proliferate rapidly once established. Meanwhile, the stakes have to initiate root and shoot growth before they can associate with AM resulting in a time lag for symbiosis to be established. How long this lag period lasts is unknown.

Table 2. Effect of method of establishment (Stake or Plantlet) on shoot and root attributes and nutrient uptake and use efficiency by *Tithonia diversifolia*. LSD values are at 0.05 probability level (n = 3).

Plant Attributes		Method of establishment		
		stake	plantlet	$LSD_{(P=0.05)}$
Photosynthetic efficiency	(Fv/Fm)	0.82	0.82	-
Leaf area index	(m^2/m^2)	1.12	2.30	0.37
Leaf biomass	(kg/ha)	814	1387	209
Stem Biomass	″	5568	13880	1807
Reproductive structures	″	630	1279	320
Total shoot biomass	″	7012	16546	2296
Total root biomass	″	839	989	ns
Total root length	(km/m^2)	3.5	5.2	ns
Specific root length	(m/g)	42	53	ns
Root length/leaf area	(m/cm^2)	0.37	0.23	0.15
Shoot N uptake	(kg/ha)	67	148	43
Shoot P uptake	″	12	21	3
Shoot K uptake	″	153	296	26
Shoot Ca uptake	″	47	82	17
Shoot Mg uptake	″	15	27	6
N use efficiency	(g/g)	88	104	15
P use efficiency	″	529	741	119
K use efficiency	″	45	56	7
Ca use efficiency	″	132	187	16
Mg use efficiency	″	442	581	96

ns = not significant.

Growth attributes

Tithonia established by plantlets had a total shoot biomass of 16.5 t/ha, which was significantly higher ($P<0.05$) than the 7 t/ha under vegetative stem cutting (stake) establishment (Table 2). The total root length and root biomass were not significantly affected by the method of establishment, although, on average, plants established by plantlets had greater root biomass, root length and specific root length indicating that *Tithonia* under this method of establishment had developed a finer root system. It is generally observed that thicker roots may be more favorable for mycorrhizal association (St John, 1980). It appears that in the case of *Tithonia* both thick and fine roots were colonized by mycorrhizae. *Tithonia* plant established by using plantlets had significantly higher shoot uptake and use efficiency of N, P, K, Ca and Mg (Table 2). The higher values of these attributes in plants established using plantlets could be attributed to greater mycorrhizal (AM) colonization under this establishment method, which might have increased the effective volume for nutrient uptake. There is evidence that nitrogen (N) is taken up by AM hyphae from inorganic sources of ammonium (Ames et al., 1983). Any direct effect of AM on NO_3^-

uptake is not known (Sieverding, 1991). Potassium (K) and Mg are often found in higher concentrations in mycorrhizal than non-mycorrhizal plants, although a direct transport of K and Mg in AM is not confirmed (Sieverding, 1991). Some experimental work suggests that in K-deficient soils the improved K uptake is related to the AM fungal species and that K may be transported by AM fungal hyphae (Sieverding and Toro, 1988). Calcium (Ca) transport in AM hyphae is not clearly confirmed; the Ca uptake is apparently affected by interaction with other elemental nutrients. However, it should also be noted that this improvement in nutrient acquisition could be as a result of relief from P stress and possibly from the uptake of some essential micronutrients. These processes will result in general improvement in growth, thus indirectly affecting the uptake of other nutrients. The differences between mycorrhizal and non-mycorrhizal plants usually disappear if the latter are supplied with a readily available P source (Bethlenfalvay and Newton, 1991; Azcón-Aguilar and Barea, 1992, Barea et al., 1992; Bethlenfalvay, 1992).

Available P (Bray-II) in the 0-5 and 5-10 cm soil depth was significantly greater in plots where *Tithonia* was established by plantlets (Table 3). The plantlet method resulted in significantly higher Ca and Mg in the profile up to 20-cm soil depth (Table 3), and a lower content of exchangeable Al (results not shown for brevity). These differences may be related to the differences in mycorrhizal associations between the plantlet and stake establishment methods. Bowen (1980) and Jehne (1980) reported that AM might play an important role as transport paths for nutrient cycling processes. AM-root external mycelia presumably can efficiently and intensively extract nutrients from a greater soil volume and thus reduce the amount of solubilized or mineralized nutrients that are chemically fixed or leached. This function of AM fungi was concentrated in the 0-20 cm depth of the soil profile where most root growth occurred.

Table 3. Effect of establishment method on root distribution, mycorrhizal association and nutrient availability down the soil profile.

Soil depth (cm)	***Method***	AM infection (%)		Spores per/100 g soil	pH (H_20)	Ca	Mg	P - Bray II (ppm)	SOM (%)	Root length (km /m²)	*Root biomass* (kg/ha)
		Fine roots	Coarse roots			(meq/100 g soil)					
0-5	Plantlet	81	67	647	5.4	3.76	0.93	10.2	11.4	1.3	121
	Stake	67	61	543	5.1	2.18	0.51	5.63	11.3	0.9	269
		(12)†					(0.17)	(0.9)		(0.2)	(121)
5-10	Plantlet	65	76	481	5.0	1.42	0.31	10.1	10.1	1.0	277
	Stake	36	62	497	4.9	0.81	0.21	3.8	9.6	0.7	151
		(10)	(11)			(0.29)	(0.04)	(2.31)		(0.2)	(65)
10-20	Plantlet	72	83	590	5.2	2.91	0.56	7.97	11.0	1.3	377
	Stake	59	54	587	5.0	1.39	0.30	3.94	11.7	1.0	237
			(21)			(0.68)	(0.16)	(2.31)			
20-40	Plantlet	75	81	198	5.1	0.86	0.22	4.82	7.0	0.8	148
	Stake	29	38	283	5.0	0.89	0.28	4.62	5.4	0.6	141
		(16)	(13)	(38)							
40-60	Plantlet	67	86	167	5.3	0.85	0.18	3.77	3.2	0.8	66
	Stake	33	16	106	5.0	0.67	0.16	3.54	3.2	0.3	41
		(18)	(9)	(38)						(0.3)	

† Where treatment effects are significant, the LSD values at 0.05 probability level are presented in parentheses (n = 3).

P fractionation

Biologically available P (H_2O-P_o, resin-P_i, and $NaHCO_3$-P_i and -P_o): The biologically available P consists of labile P 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 resin P_i and the $NaHCO_3$-P_i are considered readily available for plant uptake. At soil layers of 0-5, 5-10 and 10-20 cm, the resin P_i was significantly higher under the plantlet establishment method (Table 4). The resin P decreased sharply with increasing soil depth and accounted for 0.4 % and 0.07 % of the total soil P at the 0-5 and 40-60 cm soil layers, respectively. The $NaHCO_3$- P_i was higher under the plantlet establishment method; however, the differences were not significant except at 10-20 cm soil depth. Similar to the resin P, the $NaHCO_3$-P_i decreased sharply with increasing soil depth and accounted for 4.5% and 0.4% of the total soil P at the 0-5 and 40-60 cm soil layers, respectively. The organic fractions of the bioavailable P include the H_2O-P_o and $NaHCO_3$-P_o, which is considered "readily mineralizable" and contributes to plant-available P (Fixen and Grove, 1990). This P_o fraction includes nucleic acid-P, sugar-P, lipid-P, phytins, and other high-molecular-weight P compounds (Bowman and Cole, 1978). The H_2O-P_o contribution to the total soil P was very small and decreased steadily with depth. The plantlet establishment method had a higher H_2O-P_o at the 0-5 and 5-20 cm soil depths. The $NaHCO_3$-P_o was on average 4% of the soil total P. The method of establishment of *Tithonia* did not affect this fraction. The absence of an effect of the establishment method on $NaHCO_3$-P_o is consistent with results by Tiessen et al. (1992), who found that $NaHCO_3$-P_o was relatively constant in shifting cultivation systems on an Oxisol. The sum of all the fractions making up the bioavailable P (H_2O-P_o + resin-P_i + Total $NaHCO_3$ P) was less variable and was about the same under the two establishment methods. It decreased with increasing soil depth and ranged from 56.4 (0-5 cm) to 18.0 μg/g (40-60 cm), which was between 4 to 9% of total P (Table 4; Fig. 1).

Table 4. Distribution of P (μg/g) in various fractions at different soil depths as affected by the *Tithonia* establishment method.

Depth	Method	H_2O	Resin	Bicarbonate		NaOH		HCl 1*M*	HCl hc†		Residue	Total
		Po	Pi	Pi	Po	Pi	Po	Pi	Pi	Po	Pt	P
		(μg /g)										
0-5 cm	Plantlet	3.35	4.36	21.4	35.5	183	146	15.8	80.6	21.7	375	880
	Stake	2.35	2.55	17.3	32.6	176	252	15.4	37.1	15.0	301	828
		(0.54) ‡	(1.46)				(51)		(7.0)		(53)	(46)
5-10 cm	Plantlet	2.67	3.26	19.1	29.6	146	172	14.8	67.8	21.6	361	784
	Stake	1.71	1.66	12.8	29.1	155	130	10.0	45.7	10.9	319	717
		(0.53)	(0.92)		(5.2)			(1.8)	(14.6)	(5.8)		
10-20 cm	Plantlet	2.12	2.73	12.2	26.2	160	94.2	11.6	63.0	15.7	315	660
	Stake	1.54	1.34	7.6	25.5	130	88.3	7.6	53.4	17.3	238	603
			(0.5)	(2.3)				(2.6)	(8.3)			
20-40 cm	Plantlet	1.37	0.44	2.7	14.5	82.6	72	6.1	30.7	12.2	238	420
	Stake	1.36	0.41	2.3	13.1	58.7	130	3.2	29.2	14.0	160	457
40-60 cm	Plantlet	1.66	0.30	1.1	15.2	52.5	73	3.2	25.5	16.5	160	336
	Stake	0.83	0.23	2.0	16.2	52.4	72	4.1	26.2	8.9	154	329

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† HCl hc =Hot and concentrated HCl.

‡ Where treatment effects are significant the LSD values at 0.05 probability level are presented in parentheses (n = 3).

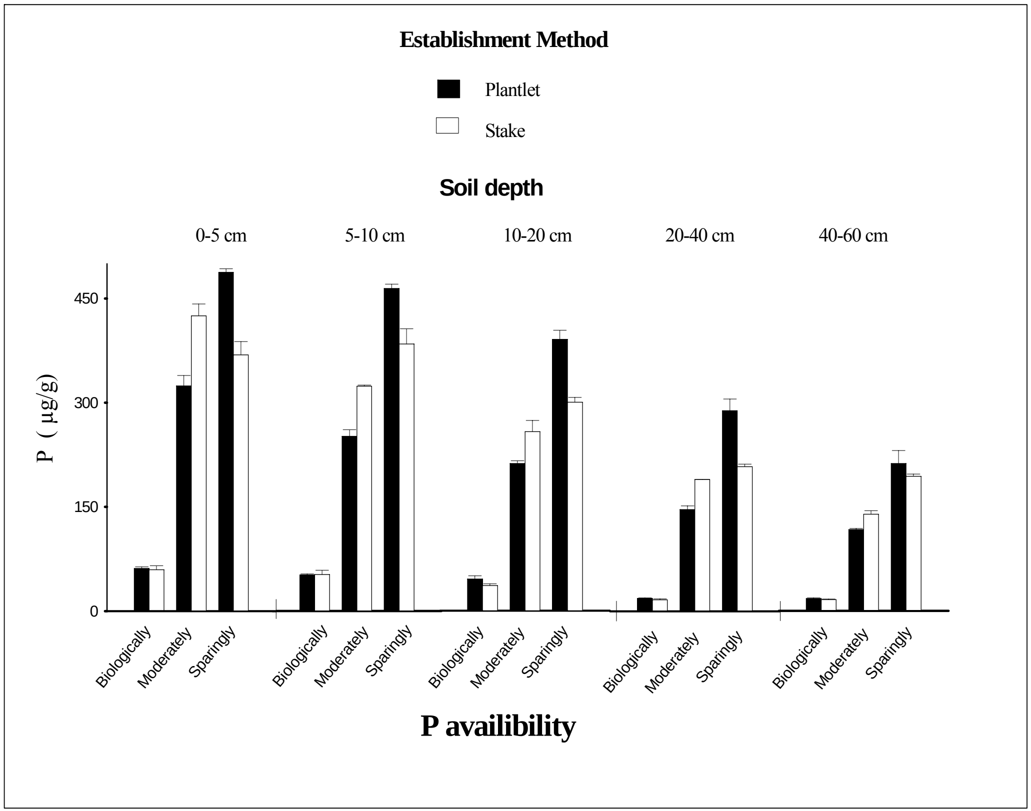

Figure 1. Distribution of three soil P fractions (ready, reversibly and sparingly available P) through 0 to 60 cm soil depth. This grouping of the fractions has been calculated from Table 4. Standard error values are shown for each mean value.

Moderately resistant P (NaOH-extractable P): This fraction is thought to be associated with humic compounds, and amorphous and some crystalline Al and Fe phosphates (Bowman and Cole, 1978). The NaOH (0.1 *M*, pH = 8.5) used completely solubilize the synthetic iron, aluminum phosphate and any labile-P_o (Anderson, 1964). A large proportion of P was recovered in this fraction, where the total NaOH (P_t) represented between 37 % and 18 % of the total soil P at the 0-5 and 40-60 soil layers, respectively (Fig 1). The plantlet establishment method resulted in high NaOH-P_i, however, the results were not significant (Table 4). The effect of the establishment method was variable on the NaOH-P_o fraction and did not follow any particular trend with increase in soil depth.

The *sparingly available P* includes the 1*M* HCl, the hot-and-concentrated HCl (P_i and P_o) and the Hedley et al. (1982) residual-P. The dilute HCl (1*M*) acid extractant is used to dissolve acid-soluble P, which consists of relatively insoluble Ca-phosphate minerals such as apatite (Williams et al., 1980). This fraction is clearly defined as Ca-associated P, since the Fe- or Al-associated P that might remain unextracted after the NaOH extraction is insoluble in acid. There was rarely any P_o in this extract. On average the dilute HCl-Pi represent about 1 % of the total soil P and was only significantly affected by the establishment method at 5-10 and 10-20 cm soil layers. It increased sharply with increasing soil depth from the 5-10 to 40-60 cm soil layers. The hot concentrated HCl is useful for distinguishing P_i and P_o in very stable residue pools. The P_o extracted at this step may also simply come from particulate organic matter that is not alkaline extractable, but it may be easily bioavailable. The plantlet establishment method resulted in a significantly higher HCl hc-P_i at the 0-5, 5-10 and 10-20 cm soil layers (Table 4). The HCl hc-P_o showed a tendency to be greater under the plantlet establishment method, but was only significantly different from the stake establishment method at 5-10 cm soil layer. The residual P is thought not to be available on a short time scale such as one or two crop cycles, but a small fraction of this pool may become available during long-term soil P transformations. The residual P represented a high proportion of the total P and was significantly affected by the establishment method at the 0-5 cm soil layer. This fraction decreased steadily with increasing soil depth.

Conclusions

This study has shown that the better method of establishing *Tithonia* as a fallow species in volcanic-ash soil is the use of bare root seedlings (plantlets) in comparison to vegetative stem cuttings (stakes). Establishment by bare root seedling resulted in increased plant growth and nutrient acquisition, which are desirable plant attributes for fallow systems because of enhanced nutrient cycling.

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Characterization of the phenomenon of soil crusting and sealing in the Andean Hillsides of Colombia: Physical and Chemical constraints

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Abstract

Soil degradation is increasing around the globe, bringing challenges that demand an investigation of influencing factors. This study investigates the new degradation phenomenon of soil crusting and sealing on volcanic Inceptisols in Andean hillsides. Crusting and sealing are commonly accepted soil deterioration factors that create unstable surface conditions and soil erosion. On an Inceptisol in Santander de Quilichao in Colombia, field trials were conducted on existing erosion run-off plots using Cassava as the main crop. During the investigation, field samplings and analyses were taken of: penetration, shear strength, infiltration and cassava yield. Results from penetration and shear strength measurements clearly showed chicken manure's significant influence on soil structure. Chicken manure generally led to structural constraints. In addition, chicken manure plots displayed a reduction of infiltration. This strengthens the hypothesis that inappropriate fertilizer management is one of the key factors of structural deterioration on Inceptisols in the Andean environment. Further research is necessary to find out sustainable soil treatments in Andean hillside farming.

Keywords*:* soil crusting, soil sealing, soil erosion, chicken manure, Inceptisols, tillage system

Introduction

Soil erosion is a major problem worldwide. Climatic impacts aside, the main reasons for soil erosion are both, inappropriate land-use and improper fertilizer management, (Lal and Stewart, 1990; Oldeman, 1990; El-Swaify, 1991) as well as socio-economic constraints (Steiner, 1994, Mueller-Saemann, 1998 *et al.*). In the process of acquiring a basic knowledge of soil degradation, efforts have focused on structural changes at the soil surface (Sumner and Miller, 1992; Sumner and Stewart, 1992; Bresson, 1995; Valentin and Bresson, 1998)). Recent observations indicate that the physical and chemical degradations of soils in the Andean zone are related to the phenomena of soil crusting and sealing.

Soil crusts are thin layers of hardened soil on the surface, occurring on dry soils (Roth, 1992; Bresson, 1995). The term "soil sealing" is used to describe superficial impermeabilities mainly occurring in wet circumstances. Soil sealing occurs if dissolved aggregates infiltrate in the soil pores leading to compact soil horizons and thus reducing infiltration (Scheffer-Schachtschabel, 1998). Both phenomena negatively impact water infiltration, and reduce air permeability and seedlings' emergence (USDA, 1996, Bajracharya *et al*., 1996, Le Bissonnais, 1990). Due to the reduction of water infiltration, the surface run-off increases; resulting in enhanced soil erosion and reduced harvest yield.

The soil crust development of Andean soils of volcanic origin is not yet well understood. Therefore, the aim of this work is to characterize the phenomenon of soil crusting on Andean Inceptisols. This project is supported by special project funds from the DAAD/Germany, the Eiselen Foundation/Germany, the BMZ/Germany and the University of Hohenheim/Germany.

Materials and Methods

Location

Field research was conducted at the Santander de Quilichao Research Station, Dep. Cauca of Colombia (3°6'N, 76° 31' W, 990 m.a.s.l). Trials had been installed on an amorphous, isohyperthermic oxic Dystropept (Inceptisol), developed from fluvially translocated partly weathered volcanic ashes. The field site has a bimodal rain distribution with two maximas in April-May and October-November, with a mean annual rainfall of 1799 mm, a rain intensity up to 330 mm/h and a mean annual temperature of 23.8°C. The measurements of soil crusting have been made on 27 Standard Erosion Experimental Plots. These plots, originally designed by the soil conservation team from the University of Hohenheim as completely randomized blocks in three repetitions, have been used since 1986 (Table 1). They were sampled at 0 to 5cm depth.

Table 1. The history of treatments in Santander de Quilichao

Treat	**93/94**	**94/95**	**95/96**	**96/97**	**97/98**	**98/99**	**99/00**	**00/01**
1	Bare fallow	Bare fallow	Bare fallow	Bare fallow	Bare fallow	Bare fallow	Bare fallow	Bare fallow
2	Cowpea, mF[1]	Cassava oF4[2]	Maize oF4	Cassava oF4	Cowpea oF4	Maize oF4	Cassava oF4	Cassava oF4
3	Cassava	Cassava	Cassava	Cassava	Cowpea	Cassava	Cassava	Cassava
4	Bush fallow	Cassava mF	Maize mF	Cassava mF	Cowpea mF	Cassava mF	Cassava mF	Cassava mF
5	Br[4] P[5]	Cassava mF	Maize mF	Cassava mF	Cowpea mF	Maize mF	Cassava oF8[3]	Cassava oF8
6	Co mF(V)[9]	Cassava	Maize	Cassava	Cowpea	Maize	Cassava	Cassava
7	Cassava Ca[6]	Cassava Ca	Maize Ch[8]	Cassava Co	Cowpea mF	Maize Ch	Cassava Ch	Cassava Ch
8	Br P	Br P	Maize mF	Br Cm[7]	Br Cm	Maize Cm	Cassava mF	Br Cm
9	Bush fallow	Bush fallow	Bush fallow	Bush fallow	Bare fallow	Bare fallow	Cassava mF	Cassava mF

[1] mF = mineral Fertilizer.
[2] oF4 = organic Fertilizer. (Chicken manure 4 t ha^{-1})
[3] oF8 = organic Fertilizer. (Chicken manure 8 t ha^{-1})
[4] Br= *Brachiaria decumbens*
[5] P = *Pueraria phaseoloides*
[6] Ca = *Centrosema acutifolium*
[7] Cm = *Centrosema macrocarpum*
[8] Ch = *Chamaecrista rotundifolia*
[9] (V) = Vetiver

Treatments

The treatments from December 1999 are described in Table 2. Before planting, the experimental plots have been limed with dolomitic lime (500 kg/ha) and plots with mineral fertilizer have been fertilized with 300 kg/ha mineral fertilizer (10N-30P-10K). Chicken manure from a local poultry farm had the following nutrient content (N: 3.43%, P: 1.82%, K: 2.73%, Ca: 3.32%, Mg: 0.64%, Fe: 1364 ppm).

To quantify and describe soil crusting and sealing, different measurement tools have been used in the field.

After planting Cassava in December 1999, field measurements with a Pocket Penetrometer (Model DIK-5560) were carried out.

Besides pentrometer measurement, a Hand Vane Tester (Model EL26-3345) was used to measure shear strength at the soil surface. Both tools were used weekly, each Penetrometer measurement 24 times and Torvane measurement 6 times per plot.

To describe direct effects of soil crusting and sealing on infiltration, a mini-rainsimulator was used in the field. Infiltration was measured by irrigating a defined soil area (32,5cm x 40cm) with a special amount of rain (90mm/h). The construction of this mini-rainsimulator enabled to subsample run-off periodically (every 5 min). The difference between irrigated amount of rain water and run-off data is defined as infiltration.

Cassava root yield in December 2000 was measured after harvest to determine the impact of soil compaction process.

Table 2. Treatments of 27 Experimental Plots in Santander de Quilichao from 1999-2001.

Treatment	Plots			Cultivation in 1999-2001
(1) Bare fallow	25	26	27	Raking at the beginning
(2.) Cassava + 4t/ha chicken manure (trad.)	2	13	19	Rototiller, 4 t/ha chicken manure
(3) Cassava monoculture	3	11	24	Rototiller, no fertilizer
(4) Cassava minimum tillage	4	17	22	No tillage, mineral fertilizer, Mulch
(5) Cassava + 8t/ha chicken manure	5	9	21	Rototiller, 8t/ha chicken manure
(6) Cassava+ 4t/ha chicken manure (Vetiver)	6	10	16	Rototiller, 4t/ha chicken manure
(7) Cassava + *Chamaecrista rotundifolia*	7	12	20	Rototiller, mineral fertilizer,
(8) Cassava rotation (*Brachiaria decumbens*	8	14	18	Rototiller, mineral fertilizer
(9) Cassava intensive tillage	28	29	30	Intensive Rototiller, mineral fertilizer

Results and Discussion

Penetrometer and Torvane

Results of Penetrometer and Torvane measurement are presented in Figures 1. During the wet season, penetration resistance was similar in all treatments. At the beginning of the dry season in May/June, differences between treatments were noted. Notably, the Cassava + 8 t/ha chicken manure became a hard soil (penetration resistance 25,4 kPa, shear strength 67 kg/cm²). Over time the minimum tillage plot generally became harder than other plots, but the well-developed and stable aggregate structure prevented negative impact on water infiltration (see below). The high amount of chicken manure caused a dispersion of clays in the wet season and results in uniform clods after drying. It was noticed that the Cassava monoculture and Cassava intensive tillage tended to be extremely soft, thus building up a single-grain structure also called pseudo-sand. Torvane measurement data tended to be similar to penetrometer measurement. Figure 1 indicates the increase in shear strength in the dry season especially within treatments of Cassava + 8 t/ha chicken manure**.**

In general, all treatments except the Cassava intensive tillage treatment had a high shear strength from June-July and turned from 13 – 22 kg/cm^2 in the wet season up to 43 – 76 kg/cm^2 in the dry season.

Infiltration

Results are presented in Figure 2. Cassava + 8t/ha Chicken manure had the lowest infiltration after 55 minutes with a final infiltration capacity of 36 mm/h.

It has to be emphasized that Cassava min. tillage as well as Cassava rotation treatment had both an excellent infiltration capacity. Minimum tillage influenced the soil structure positively in the way that aggregation over a long time period is supported. This helped to build up a soil structure, as also the mulch at the surface led to a better infiltration.

Yield

Results of harvest data are presented in Table 3. Overall, the best root yields were found in Cassava 4t/ha chicken manure and Cassava rotation. High Cassava root yields in these treatments are due to improved soil conditions such as moderate soil hardening, sufficient fertilization, enhanced soil aggregation and high water infiltration. In contrast, the lowest yields were found with Cassava monoculture and Cassava intensive tillage treatments. The Cassava monoculture treatment is characterized by a low nutrient content in the soil through insufficient fertilization over a long period of time.

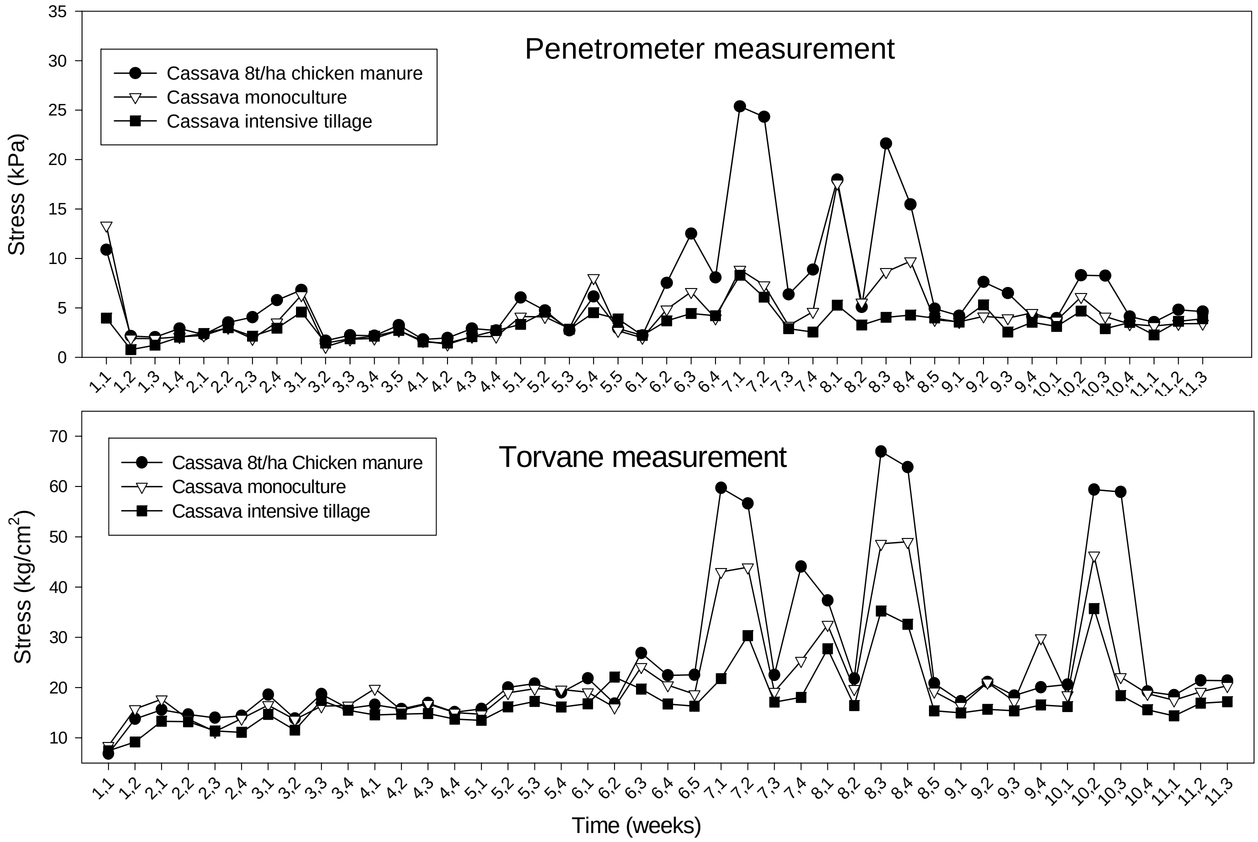

Figure 1: Influence of soil treatment and crop management on penetration resistance and shear strength, Santander de Quilichao, Jan-Nov 2000

The single grain structure and low infiltration capacity contributed to low root yield. The Cassava intensive tillage treatment is characterized by a breakdown of the pore system. Thus, leading to a lack of infiltration and reduced yields. In both treatments, roots were very small and economically worthless. Cassava 8 t/ha chicken manure had high amounts of plant biomass but hard soil structure, preventing optimal development of Cassava roots. In Cassava minimum tillage treatment, root growth was limited to the area loosened before planting. Therefore yields in both treatments were lower than in Cassava rotation and Cassava 4 t/ha chicken manure

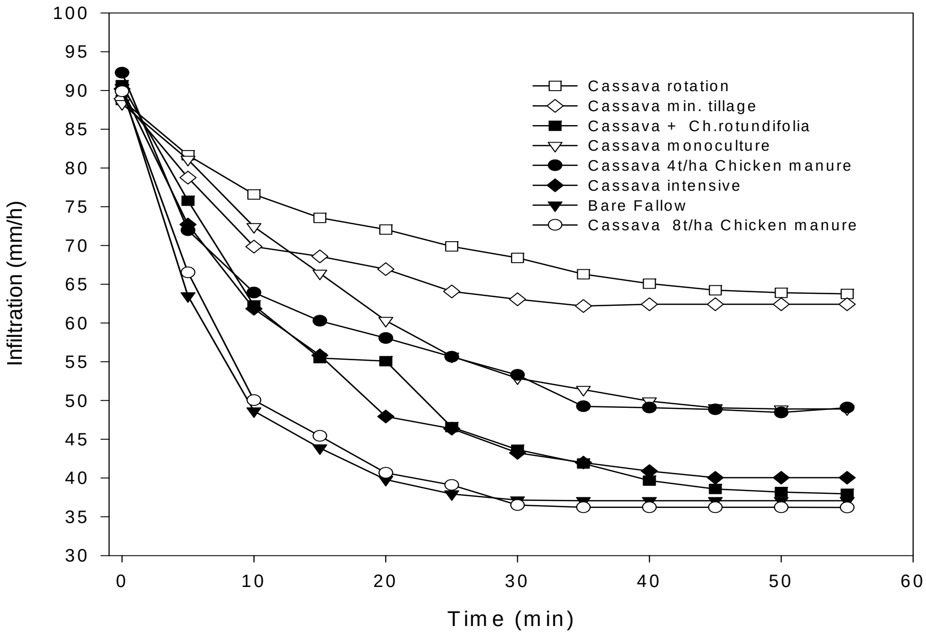

Figure 2. Effect of treatment on infiltration measured by rainsimulation, March 2000. Location: Santander de Quilichao**.**

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Table 3. Cassava root yields, Santander de Quilichao, 2000.

Treatment	Yield (t/ha)
Cassava monoculture	4.33 a
Cassava int. tillage	11.98 b
Cassava + *Chamaechrista rotundifolia*	21.05 c
Cassava (V) 4t/ha chicken manure	21.90 c
Cassava 8 t/ha chicken manure	23.17 cd
Cassava minimum tillage	27.01 cd
Cassava rotation (*Brachiaria decumbens* + *Centrosema macrocarpum*)	30.59 e
Cassava 4 t\ha chicken manure	30.92 e

Means followed by different letters within the column are significant at 0.05 probability level (Duncan test).

Discussion

In summary, penetration resistance and shear strength showed no risk of structural damage in the wet season. This worsened in the dry season when Chicken manure treatment turned into hard and impermeable soils. Although, the minimum tillage treatment had high penetration resistance and high shear strength values, this caused no deterioration because of a good aggregation status. This can clearly be seen in the results of infiltration measurement. Monoculture and intensive tillage had neither high penetration resistance nor high shear strength. In contrast, these treatments easily built up the so-called pseudo-sand that lead to high proportions of small aggregates, and thus to high amounts of soil erosion. The more modern techniques of Minimum tillage and Cassava rotation had the best and most sustainable status. Those treatments had a good aggregation, showed adequate infiltration rates and did not suffer from human induced fertilizer damage, e.g. soil hardening due to chicken manure or deterioration of soil matrix through intensive tillage. Chicken manure, especially 8 t/ha, had a severe impact on soil surface.

Further research is needed to specify the reasons why chicken manure has such an influence on aggregates. It is unclear which dispersion agent might be that leads to aggregate dispersion. Furthermore, structural changes through intensive tillage or minimum tillage have to be looked at more closely in order to ascertain how severely aggregate breakdown affects plant growth on Inceptisols.

Conclusion

Results from penetration and shear strength measurement showed the marked influence of chicken manure on soil structure. Chicken manure generally resulted in a deterioration of soil's structural status. A reduction of infiltration, especially in chicken manure plots, substantiates the hypothesis that inappropriate fertilizer management is one of the key factors in structural deterioration on Inceptisols. Dispersion of clays, generally cited as the main reason for soil sealing, is influenced by the impact of chicken manure. Further research will need to focus on the impact of fertilizers on the soil surface in order to design sustainable land-use systems for Andean hillside farming.

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Report for IDRC 'Folk Ecology' Project

Increasing understanding of local ecological knowledge and strengthening interactions with formal science strengthened.

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Rationale: The project is testing a community-based interactive learning approach, which aims to improve and sustain agricultural productivity by facilitating a common understanding between scientists, farmers and other stakeholders about how agro-ecosystems operate and how best to manage them.

The major goal of the project is to develop innovative and interactive learning tools to facilitate the exchange of knowledge and skills between farmers, scientists and other agricultural knowledge brokers. The specific focus of the project is to broaden farmers' soil fertility management strategies by incorporating scientific insights of soil biology and fertility into their repertoire of folk knowledge and practical skills.

A parallel goal is to strengthen the understanding of indigenous agro-ecological knowledge among scientists, extensionists and other stakeholders and to elucidate the local realities and complexities that determine farmers' decision making. This interactive and multidirectional communication process provides opportunities for both farmers and scientists to question and validate their knowledge. It also presents a mechanism for disseminating and sharing useful local knowledge between different groups of agricultural stakeholders.

Progress: The major activities of the first year were largely exploratory in nature, covering three main areas: 1) community studies and learning activities (this Activity section), and 2) development of methodologies for the research and for farmers to share information with each other and with researchers, and 3) monitoring and documentation (for both, see Activity 2.2 "Community-based learning and dissemination strategy developed"). The coming year will see much more emphasis on communication strategies, building on existing knowledge, and broadening the scope of farmer-to-farmer exchanges.

Community studies and learning activities: The four study sites all have some previous exposure to either TSBF or local NGO's that had worked on soil fertility management. They cover a range of agro-ecological conditions and ethnicities, and thereby present an interesting and representative diversity of communities in Western Kenya (Box 1).

Box 1. Overview of study sites

Site name	District	Ethnicity	Pop. Density (people / km^2)	Annual Precip. (mm)
Ebusiloli	Vihiga	Luyia	1100	1800-2000
Bukhalalire	Busia		384	1270-1790
Muyafwa	Busia		365	1270-1790
Aludeka	Teso	Teso	436	760-1015

The project began with introductory, community discussions, which led into exploratory group work to assess the types and extent of knowledge and assumptions held locally about soil fertility and soil ecological processes. Once this baseline study of 'folk ecological' knowledge was completed, there were various follow-up activities concentrating on key informants and specialist groups.

Community and key informant interviews and seminars

The introduction of the project centred on community interviews held in the four sites. These events, facilitated by a multi-disciplinary team had as their objectives:

- Determining the local "vocabulary" used for discussing soil fertility
- Identifying concepts locally related to soil fertility knowledge (classification, process, relationships)
- Identifying the elements of locally understood "common sense" related to soil fertility
- Identifying the individuals or groups who possess specialised knowledge of soil fertility and its management
- Identifying the assumptions or "rules" of local soil fertility knowledge.

Following the initial meetings, farmers and researchers alike were eager that findings be returned to initial groups for discussion and validation. The collective findings of the community interviews were synthesised and presented back to the communities in open seminar events, which led to follow up activities on locally important themes. In particular, transect walks and other ground-truthing activities helped both broaden the involvement of community members beyond the participants of the initial meetings and to build rapport with potential key informants with specialist knowledge.

Key findings from the baseline study activities include:

- Local soil types were readily identifiable. Local descriptions distinguished more soil types than were recognised as distinct soils by scientists. Soil maps are based on 'expert opinion' but do not reflect the high familiarity and local knowledge of farmers in daily contact with their land. Individual farmers also adapt common local names to the soils found on their own land.
- Soil names reflected features of the surface layer: colour, texture, depth, fertility, erosion, first user or settler (i.e. history). Soil was understood holistically, as "mother", "ourselves", "life", or "wealth", and not just as a physical surface on which life is found. The soil was more commonly acknowledged as the source of life and wealth rather than alive or a type of wealth in its own right.
- Farmers identified a diversity of directly observable, constituent parts of soil (living and non-living), including minerals, sand, silt, decaying things, worms, insects, moisture, and temperature. The presence of invisible or microscopic aspects of the soil was observed indirectly, through the growth of specific wild plants, or through crop performance.
- No single local terminology exists to describe soils' fertility status, and there was no significant gender difference in the use vocabulary or concepts. A linguistic difference was that the Teso word "*aboseteit*" referred to soil fertility and things that enhance it, while Luyia used a more general word "*obunulu*" to denote both a fertile soil and rich, fatty meat.
- Multiple analogies were used when describing soil fertility, including paired opposites like "healthy / sick or hungry", "strong / weak or tired", "young / old", "moist / dry". The aspects considered important in describing fertility were texture (light, loose soils were preferred to heavier ones, which would stick on implements), colour (darker soils were considered more fertile), health or energy (as seen in crop performance, "weak", "old", or "tired" soils need to rest or to be fed).
- Many locally known plants indicate high or low soil fertility. These indicator species, however, are not universal and their interpretation may vary. The presence of certain uncommon species may be enough to imply "high" fertility, while the relative performance of widespread species is often compared to give an indication of fertility. Generally, indicator species appear to reflect "inherent" soil properties more than trends of improvement or decline. Knowledge of plant indicators is both widely accepted and highly debated, and will be investigated further. In

particular, the distribution and use of this knowledge is being more intensively studied by the Master's student Nelson Otwoma (see "Training" below).

- Respondents assumed that without inputs soils become "poor" or "worthless". It was also widely believed that using inorganic fertilisers encourages crops to overexploit the soil's energy and can quickly "exhaust" or "bleach" the soil. Because organic inputs have longer residual effects than inorganic ones, respondents felt that both must be used in combination, or one will disrupt a desired balance of elements in the soil.
- Applying "farmyard manure" and constructing terraces were the most common soil management interventions. There was extreme individual variation between farmers in terms of what materials were included in "manure" and the manner in which they were managed while decomposing or applied to cropland. Manure management will be a major topic for further investigation. Only farmers in Aludeka did not commonly use manure, since land is relatively abundant and trypanosomiasis limits cattle keeping.

Major changes in managing soil fertility over the last fifty years include the introduction of inorganic fertiliser, construction of terraces, systematic use of livestock manure, fallow trees and compost. Traditional farming encompassed fallowing, shifting cultivation and slash-and-burn as major practices. Practices that were introduced by the government and had been or were being abandoned include crop rotation on an annual basis, since land is too limiting. The follow-up activities with key informants have particularly emphasised participant observation of management practices, which are notoriously difficult to discuss in the abstract and are more meaningfully observed on the ground.

Issues relating to dissemination and learning

Traditionally, information was disseminated communally and government did not have a role in provision of services like agricultural extension. Farmers learned mainly through observation, apprenticeship and experience, resources were abundant and knowledge on the environment was extensive. Today, farmers have more knowledge on intensive agriculture but use of this knowledge is constrained by limited access to key resources, including land, biomass and livestock. Many farmers reported that reduced landholdings and the difficulty of acquiring new land limit their ability to fully exploit their traditional knowledge of soils and their management. As a result of land scarcity, there was little correspondence between soil type and crops grown, even when farmers stated that a given soil was not well suited to the crop being grown. Resource constraints will almost certainly limit the relevance and amount of traditional knowledge being passed on to later generations.

Usually, information about meetings and other research events is given out to relatively few farmers. This information later reaches their friends and also neighbours and relatives. In addition, most of such events are held in the open where most passers-by see. Nevertheless, some farmers did not feel encouraged to attend these events. As an example, a woman who lives adjacent to a TSBF research plot in Emuhaya said: "I would like to attend research events, …but I have no one to 'follow' (i.e. orientate her to them)". She was aware that research on soil fertility had been continuing for long in her village. She also knew it would be beneficial but had never regarded herself to be part of the process.

Specifically relating to dissemination of knowledge on soil fertility, there was a common feeling amongst participants in the four sites was that there was inadequate awareness creation on soil fertility research. Many farmers did not understand how they would participate or even directly gain. It is as a result of this that many farmers still expect money or other handouts from researchers. Farmers suggested some steps that could be useful in enhancing the spread of knowledge on soil fertility:

- Experimental and demonstration plots should be soil-based; located in different soil types found in the study areas, which would assist farmers to relate the practices to their situation easily. Participants observed that some trial plots may have performed better than others due to differences in soils and that some preferred practises would be inapplicable in certain soils. At present, TSBF hires trial plots depending on their availability, adequacy of size and shape of trial plot, willingness of farmers to rent their plots out and to co-operate, security, accessibility, absence of such barriers as rocks and termite mounts, representativeness of agro-ecological zones.

- Plots should bear well-labelled posters showing procedures on experiments and stating that it is pure “trial” and not something automatically beneficial or “interesting” to farmers. One farmer suggested that trial plots that are managed by the researcher should be hidden from busy roads so that they are not seen by passers-by especially when they perform poorly (as was the case with some plots in 2000).
- Technologies should be better adapted to farmer conditions. Participants in focus group discussions suggested that green manure species that mature within a shorter period and which can be inter-planted with crops and/or eaten would be preferred. Such technologies should be developed so that they can be broadcast in the farm, without necessarily having to be planted carefully in lines or rows. The main concern was that new technologies should not require rigorous skill and experience.
- Group-based approaches, including collectively identified and run plots can be effective venues and tools for passing new technologies to farmers. In Emuhaya, several ‘Farmer Field Schools’ have emerged spontaneously to broaden community participation beyond the original, rather exclusive ‘Adaptive Research Farmer Groups’. Local level meetings where farmers could exchange ideas have been tried in the past in other sites, but have not been sustained. It is necessary to involve many people in activities of dissemination. Awareness can be done through field days, demonstrations, visits or exposure tours to other areas.
- It is widely felt that individualistic behaviour and the absence of ‘traditional’ practices that once united communities (beer brewing, labour sharing, etc.) undermine collective endeavours today. It is certainly true that few activities promote positive competition amongst farmers. Household differences and clan rivalries are also major sources of division, although most key informants felt that they could be overcome with good leadership.
- Low interest in research work was partly attributed to poor leadership. Researchers, like local leaders were said to “stand before farmers and address them”. The two were therefore similar. Just as local leaders never delivered on their promises, research was initially seen to be unproductive. For instance, a bean variety that is suitable for N Eastern Kenya was planted on one of the key informant’s plot in Emuhaya. As with the poorly performing trial plots in 2000, this inadvertently created the impression that “if a specialist’s work failed, what is the point in learning how to copy it?”
- Farmers have ‘tools’ of measuring researchers. Those with meaningful intentions and hardworking are known and easily draw farmers’ attention. Farmers should be consulted when deciding on ways of teaching.
- Farmer research groups have limited participation of non-members through charging of subscriptions. Most farmers perceive subscription as extortion and expressed their objection that “information from research bodies should not be passed through such groups”.

Training and capacity building: To investigate the dynamics of how agro-ecological knowledge is generated and shared within a community, two master’s level research activities are being conducted. The first project takes a more anthropological approach to understanding the role of local indicators of soil fertility change (particularly plant species and plant growth traits) and the degree to which different groups or individuals have come to recognise given indicators, or value the information that those indicators impart. The second study (still in preparation) will take a more ethnobotanical approach to understanding the distribution and relevance of indicator species, and will likely be situated in a contrasting environment.

Student Thesis (submission by end 2003)

“The role of indigenous knowledge in the management of soil fertility among smallholder farmers of Emuhaya division, Vihiga district.”

Nelson Juma Otwoma
University of Nairobi

Justification: This study will add to the search for information on soil fertility management being pursued by many researchers and planners. Besides, there is a growing appreciation and recognition of the importance of local or indigenous knowledge in the sustainable use of natural resources. But the lack of information stands in the way of good understanding of these methods. By taking time and effort to document the systems, they become accessible to change agents and client groups (Brokensha et al. 1999: xv).

The study does not, however, pretend that local knowledge and practices has the quick solution to the many problems facing farmers in the area of soil fertility management. Far from that, it recognizes the importance of integrated knowledge systems (modern and indigenous) and while focusing on the latter the study will pay attention to the former.

The Folk Ecology Project (that provides a background for this study) needs specific information that can facilitate the integration of two knowledge systems (modern and indigenous), which eventually will enable scientific information to become a component of the larger pool of local knowledge to be more efficiently applied by the local people themselves particularly in the area of soil management.

The Emuhaya division study site lies within a region, which has poor subsistence economy due to unreliable rainfall and highly fragile soils. Smallholder farmers in this region face the double tragedy of environmental degradation and increasing demand for food. While the extension workers and other agencies could be willing to assist, their efforts could be hampered by the prevailing low socio-economic status, especially among the small farmers. This, therefore, calls for the need to carry out a study, which could inform the donor community or, more importantly, the policy makers and communities themselves to enable them formulate a broad strategy within which resources can be more effectively focused.

The findings of this study could, therefore, enable governments, policy-making bodies, non-governmental organizations and donors to formulate and design strategies that can alleviate suffering emanating from soil nutrient depletion among smallholder farmers. Agricultural research institutions can also base on the findings to institute the intervention programmes that could improve the conditions of smallholder farmers so that they are not left vulnerable to adverse environmental effects. Extension workers can also use the report to enable them understand the indigenous knowledge perspective of soil fertility management practices.

In addition, the findings are also potentially replicable. Brokensha *et al* (1999) argue that it is quite apparent that indigenous innovations, which are found to be effective in one part of the globe, can be equally effective when made available to populations in similar ecological conditions in other parts of the world. The documentation of the vast amount of unrecorded; often rapidly disappearing indigenous knowledge could provide the basis for many effective development interventions, if this knowledge could be shared.

The general objective of the study is to describe indigenous knowledge of soils and how it relates to the management of soil fertility in the study area. Specific objectives include:

i) To identity the local diagnostic criteria for differentiating soil types among smallholder farmers within the study area.
ii) To identify local indicators for discerning soil nutrient depletion or loss among the study population.
iii) To investigate the soil fertility management practices used by smallholder farmers in the study area.

Methods: The field research phase of this study covered the long rains growing season of 2002, allowing the student to follow the on-farm activities and decision-making processes of key informants responding to various indicators of crop performance and soil fertility change. As such, it was expected to provide a useful window on an important aspect of local ecological knowledge and the extent to which it can (or does) inform local practice.

Many of the older key informants, for example, have stressed that much of the knowledge they have acquired about changing agricultural conditions is no longer particularly relevant to their livelihoods for the simple reason that their land base is now so constrained that there are fewer opportunities to match crops to given micro-sites on farm. The adapted knowledge of younger farmers, however, indicates that local soil variability can still be profitably exploited with different management strategies, at least by some classes of motivated individuals.

Student Thesis (submission by 2004)

Identification of local plants as indicators of soil quality in the Eastern African region

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Rationale: Local plants as indicators of soil quality, like other biological indicators of soil quality, simultaneously reflect changes in the physical, chemical and biological characteristics of the soil. Because of their integrative nature they are often better early warning indicators than other conventional methods to detect changes in soil quality.

Natural and agricultural systems respond in a similar way to degradation and regeneration processes through the ecological principle of succession. During succession, plants and soil organisms that are best adapted, gradually substitute those least adapted, because of the selection exerted by changes in soil characteristics (i.e. some plants can tolerate more degraded soils than others, etc.). If we are able to identify local plants used by farmers to characterize their soils across a region we may be able to organize this information and identify trends which can provide insights about their potential use in making decisions about land management.

CIAT's work in Latin America has shown the important role played by local plants as indicators of soil quality (Barrios and Escobar, 1998). This document proposes a collaborative activity among CIAT, SWNM and AHI scientists to identify local plants used as indicators of soil quality in the Eastern Africa region using the AHI sites as a representative sample (i.e. Kenya, Tanzania, Uganda).

This collaborative work will lead to the preparation of a table with local plants used as indicators of soil quality to be included as a contribution of AHI to Guide #1 "Identifying and Classifying Local Indicators of Soil Quality (LISQ), Eastern Africa Edition (2001)". Within this context, work will clearly identify the localities where the observations are being conducted, and will select key informants and elder representatives of the different farmer communities in the study area for group analysis (brainstorming) sessions. The following questions will guide the discussion for identifying and prioritizing local plants as indicators of soil quality from the local knowledge base:

i) Are there any local plants (weeds, shrubs, trees) that only grow in fertile soils?
ii) Are there any local plants (weeds, shrubs, trees) that only grow in poor soils?
iii) Are there any local plants (weeds, shrubs, trees) that grow in all soils but that according to their growth, vigor and color can be used as indicator of the soil condition?
iv) If you were buying a new plot which plants would you use to characterize the quality of such plot for agricultural purposes?
v) After several seasons of cropping, you decide to leave your plot fallow by allowing natural regeneration of the native vegetation to take place. At what stage in that regeneration do you go back to cultivation? Are there any plants that indicate that your plot is ready for cultivation again?

Information gathered will be organized and prioritized using pair-wise ranking in order to provide a list of most important to least important of all the plants used as indicators of soil quality.

Evaluation of current ISFM options by participatory and formal economic methods

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Rationale: Declining soil fertility problem is the single greatest threat to food security and livelihoods in Western Kenya. Findings of most soil fertility research work in the region indicate that the soils of this region are generally deficient in Nitrogen and Phosphorus nutrients. This problem has been caused by high population density and poor farming methods. For instance in Emuhaya area, farmers continuously crop their fields with minimal use of inorganic or organic fertilizers. This type of farming can not be sustained in the long run and if not checked could lead to deterioration in the farming environment. Some of the indicators of a deteriorating environment are; sharp decline of crop harvests, high incidences of crop and animal pests and diseases, frequent famine, deteriorating farm incomes among others.

Progress: A baseline survey of soil fertility management practices and socio-economic conditions was completed and analysed for 314 farmers in the West Kenya site. The methodology was shared with the Ugandan and Tanzanian sites. These data are being compiled and analysed along with comparable studies conducted at the other BMZ project sites in West Africa (Togo and Benin) to produce a scientific paper relating soil fertility management practices to the contrasting socio-economic and agro-ecological conditions of the sites.

Farmers, extension, and KARI-Kakamega field staff were trained in participatory monitoring and evaluation methods. Several forms of farmer recording keeping were introduced in 2001 to monitor and evaluate progress with the soil fertility management technologies. However, lack of funds has limited follow-up, which has lead to widely varying levels of farmer interest and disparate standards of data collection.

A good number of partners have since initiated trials in the region whose main goal was to enable farmers to produce agricultural products while reversing nutrient depletion on their soils. The purpose of this was to increase the farmer's capacity to develop, adapt and use integrated nutrient management strategies. The integrated soil fertility management options tried include; biomass transfer using Tithonia diversifolia, use of improved fallow plants (Mucuna, Crotolaria grahamiana, C. ochroleuca, C. paulina, Canavalia, Sesbania sesban etc), use of high quality compost, integration of inorganics and organics. The partners in this research include; the African Highlands Initiative (AHI), Tropical Soil Biology & Fertility Programme (TSBF), International Centre for Research in Agroforestry (ICRAF), Kenya Forestry Research Institute (KEFRI), Kenya Agricultural Research Institute (KARI), Ministry of Agriculture Extension service and Farmer research groups. The research work was implemented through the framework of participatory technology development and transfer.

The initial target number of farms was 60 located in 5 villages of Ebusiloli sub-location of Bunyore East location in Emuhaya division of Vihiga district. The work was implemented through the farmer research group framework, which focused the village as the unit of research work. Each village was organized into a research group with elected officials managing their respective groups.

The specific objectives of this study are:

i) To quantify the costs and benefits of the practiced ISFM technologies in order to show the profitability of each technology.
ii) To conduct participatory ranking of the ISFM options based on farmers criteria and perceptions.
iii) To identify the constraints facing the ISFM practitioners and possible solutions to overcome them in order to improve the adoption of technologies being practiced.
iv) To build the capacity of the farmer field schools to innovate and share the results for collective action.

The FFS Framework: The farmer field schools work together to implement the study. Suitable farms were identified and the owner contracted using the procedures of TSBF and ICRAF being currently used to implement other trials. The decision support systems (DSS) layout for the trial (see section 2.3) in Emuhaya was adopted. There is concern from the farmers that treatment plot sizes need to be increased for more visibility. They propose to have 10 m x 10 m plots. The farmer field schools propose to include the local (indigenous) plants and test them as well. The treatments will be randomly selected and established.

Formal economic analysis of current ISFM options

Rationale: In sub-Saharan African countries like Kenya, small-scale farmers account for about 70% of the over all production and produce more than 75% of the total food crops. Soil erosion, depletion of ground cover due to overgrazing and nutrient depletion due to continuous cropping has lead to low living standards among the majority of the rural households. The depletion of the natural resources (land and forests) as a result of population pressure and continuous cropping in the study area does not augur well for the future generations who are expected to live on and derive their subsistence from such lands.

To reverse the trend of rapid decline in the quality of soil and the physical environment, large investment in soil fertility technologies and soil conservation works is needed. This study seeks to justify and warrant such investment by providing quantitative and empirical evidence of the importance, appropriateness and economic competitiveness of agroforestry-based and other integrated soil fertility management (ISFM) technologies as strategies that are potentially capable of solving and alleviating productivity problems. The findings will be useful in terms of postulating suggestions to policy makers pertaining the incentives and institutions that can be put in place by the government and other stake holders to enhance the promotion and expansion of the emerging technologies of addressing soil nutrient depletion.

Training and capacity building: Two master's level research projects are currently on-going. The first uses the policy analysis matrix (PAM) technique to evaluate the private and public benefits and costs of different ISFM options. This approach is particularly useful for examining the role of transaction costs and market failures in influencing profitability of new technologies. The second study determines whether the soil fertility management and livelihood enhancement needs of different classes of farmers are being met with the ISFM options currently available to them, by contrasting the profitability of different options (using gross margin analysis).

Student Thesis (submission in early 2003)

The Competitiveness of Agroforestry-based and other Soil Fertility Enhancement Technologies for Smallholder Food Production in Western Kenya.

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Abstract: Most countries in sub-Saharan Africa have been faced with persistent food insecurity accompanied by low and declining agricultural production and productivity. Although in Kenya population growth has been on the decline, increased settlement on arable land has exerted pressure and heavy demands on natural resources especially land. As a consequence, continuous cropping has been very common among majority of the smallholder farmers leading to soil nutrient depletion. Many studies in Kenya have shown that soil fertility depletion among smallholder farms is responsible for the persistent food insecurity and declining per-capita food production.

In order to address the soil fertility problem, researchers in International Centre for Research in Agroforestry (ICRAF) and Tropical Soil Biology and Fertility programme (TSBF) have been able to develop and promote agroforestry-based technologies. They include biomass transfer and improved fallows.

Although these agro forestry based technologies together with *Minjingu* rock phosphate are being used by farmers in western Kenya, little is known about their economic competitiveness in terms of how efficient resources are being used to produce food under these soil fertility enhancement technologies. The proposed study is an attempt to bridge the above-mentioned gap in knowledge by providing a quantitative evidence of farm level profitability (both private and social) of food production under the above mentioned soil fertility replenishment technologies. The study will be carried out in Siaya and Vihiga districts, western Kenya.

The Policy analysis methodology (PAM) will be used to analyse both primary and secondary data. A multi stage stratified sampling method will be used to select a total of one hundred and twenty farmers, sixty from each of the two districts. The selected farmers will be interviewed using structured questionnaires.

A reconnaissance survey will be conducted in the area of study to identify the farmers to be interviewed. A questionnaire pre-test will be done on farmers in the area but the sample of the pre-test farmers will be outside the sampling frame.

The over-all objective of the study will be to determine the competitiveness of both agro- forestry based soil enhancement technologies and use of Minjingu Rock Phosphates for smallholder food production. The specific objectives will include:

i) To determine the financial profitability of food production under agroforestry-based technologies (improved fallows and biomass transfer) and *Minjingu* rock phosphate as alternative soil nutrient replenishment technologies.
ii) To determine the social profitability of food production under agroforestry-based technologies and *Minjingu* rock phosphates as strategies of the soil fertility enhancement.
iii) To compare the competitiveness of both inorganic fertilizers and agroforestry-based technologies for food production.
iv) To compare the profitability of maize and horticultural production using agroforestry based technologies.

Student Thesis (submission by 2004)

Assessment of adoption potential of soil fertility improvement technologies in Chuka Division, Meru South, Kenya

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Abstract: Declining soil fertility is a key problem faced by farmers in Eastern Kenya. The problem has been worsened by increased population growth and at the same time, high demand for agricultural produce. To solve the problem land users are being encouraged to adopt soil fertility improvement technologies, which use locally available resources. In on-going demonstration trials at Kirege primary school (Chuka division), a number of such technologies are being demonstrated for which farmers are being encouraged to voluntarily select the technologies that they would wish to adopt on their farms. This study will therefore set out to evaluate the extent of the technology adoption as well as how the farmers modify such technologies, and the gender issues in dissemination and adoption of the technologies. To do this, a farmer follow-up study will be carried out in Chuka division over a period of two cropping seasons. Data will be collected using farm surveys, which include both formal and informal surveys, on-farm trials and visual records. Gross margin analysis will be used to determine the most profitable treatments / technologies. Lastly, logistic regression analysis will be used to determine important variables in the adoption of a new technology.

The overall objective of the study is to increase food production by better understanding the adoption of technologies capable of improving soil fertility status in the smallholder cropping systems of central and eastern Kenya. The specific objectives are:

- i) How do different socio-economic classes of farmers in Chuka, eastern Kenya differ in their soil fertility improvement needs?
- ii) Which soil fertility management technologies have been most adopted by different classes of farmers?
- iii) How profitable, agronomically beneficial, and labour demanding are the soil fertility management technologies being used by farmers in Chuka?
- iv) How are the farmers of different genders or socio-economic classes modifying the soil fertility management technologies?
- v) How are the farmers of different genders or socio-economic classes disseminating the soil fertility management technologies?

Food Policy (in Press)

Integrated soil fertility management: evidence on adoption and impact in African smallholder agriculture

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Abstract: This paper reviews current organic nutrient management practices and their integration with mineral fertilizers in Sub-Saharan Africa with a view to understanding the potential impacts on a range of input markets. A number of different organic nutrient management practices have been found to be technically and financially beneficial, but they differ considerably as to their effectiveness and resource requirements. Review of African smallholder experiences with integrated soil fertility management practices finds growing use, both indigenously and through participation in agricultural projects. Patterns of use vary considerably across heterogeneous agroecological conditions, communities and households. The potential for integrated soil fertility management to expand markets for organic inputs, labor, credit, and fertilizer is explored. We hypothesize that markets for organic markets are hampered by inherent constraints such as bulkiness and effects on fertilizer markets are conceivably important, although no good empirical evidence yet exists on these important points.

1. Introduction

There has been renewed attention on soil fertility replenishment in Sub-Saharan Africa as critical to the process of poverty alleviation, as symbolized clearly by the award of the 2002 World Food Prize to Pedro Sanchez, a pioneer in the field. Soil fertility is crucial because in Africa poverty is mainly a rural phenomenon. With 70% of the population in the rural areas and 60% of those living below the poverty line, a whopping 85% of the poor are found in rural areas (Mwabu and Thorbecke, 2001). Since over 95% of the rural population is engaged in agriculture to some degree, any short to medium term poverty reduction strategy that ignores agriculture is doomed to fail.

In many places, the rural poor cannot expand land holdings. Per capita arable land in Sub-Saharan Africa has shrunk dramatically from .53 to .35 hectares between 1970 and 2000 (FAOSTAT, 2002). Accelerated and sustainable agricultural intensification is required. Returns per unit land must increase in order to provide sufficient food for the (rural and urban) poor and output per worker must rise in order to lift the incomes of the poor. This has clearly not taken place as evidenced by the stagnant crop yields and per capita indices for agricultural and food production. For example, per capita agriculture, food, cereal, and livestock production indices are all below levels from 1990. While the first steps to reverse this trend are hotly debated, it is certain that increased agricultural productivity and improved rural livelihoods cannot occur without investment in soil fertility.

There is no shortage of evidence showing the dismal state of Africa's soils. African soils exhibit a variety of constraints, among them: physical soil loss from erosion, nutrient deficiency, low organic matter, aluminum and iron toxicity, acidity, crusting, and moisture stress. Some of these constraints occur naturally in some tropical soils, but they are exacerbated by severe degradation processes. Degradation of some form is pervasive on the continent, with less than 20% of soils said to be unaffected by degradation (FAOSTAT, 2002) and about two-thirds of agricultural land to be degraded (Oldeman et al., 1991). About 85% of degradation is attributed to water and wind erosion, with the rest being mainly *in situ* chemical degradation (Oldeman et al., 1991).

The lack of nutrient inputs among smallholder African farmers exacerbates the nutrient deficiency of soils. Fertilizer use was never high in Africa. Exchange rate devaluations and the termination of government fertilizer subsidy programs throughout the continent over the past fifteen years have sharply increased the real price of mineral fertilizers, putting them beyond the reach of most small farmers in Africa, at least at anything approaching recommended application levels. As a result, while the rest of the world averages 97 kilograms of fertilizer per hectare, in Africa, only 9 kilograms are applied to the average hectare of land (Gruhn et al, 2000). The rate is lowest in central Africa (2 kg per ha) and in the Sahel (5 kg per ha). Even when fertilizer is combined with other organic sources, studies throughout the continent have found high negative nutrient balances to occur in nearly all countries (Henao and Baanante, 2001). The estimated losses, due to erosion, leaching, and crop harvests are sometimes staggering, at over 60 – 100 kg of N, P, and K per hectare each year in Western and Eastern Africa (e.g. Stoorvogel and Smaling, 1990; de Jager et al. 1998).

Integrated soil fertility management (ISFM), developed more fully in section 3, is being widely studied and is rapidly becoming more accepted by development and extension programs in Sub-Saharan Africa, as well as, most importantly, by smallholder farmers in Sub-Saharan Africa. This paper begins with a brief setting of the context, demonstrating the key variations in agro-ecology, market opportunities, and farming systems in Africa and how these will condition the incentives for ISFM. The following section synthesizes evidence to date on the biological and financial impacts of organic nutrient practices and ISFM. Section 4 synthesizes available evidence on markets for organic nutrients, including supporting markets for seed, labor and credit. Section 5 provides a comprehensive summary of evidence on farmer investment in and management of organic nutrients and ISFM. Lastly, we conclude the paper with implications for research priorities, design and dissemination of ISFM, and policy reform.

2. Potential for mineral and organic inputs in SSA

Sub-Saharan Africa is very heterogeneous in terms of soils, climate, agricultural potential, market access, and population density. These differences influence the types of organic nutrients that are technically feasible to produce, the types of crops that will benefit from such application, opportunity costs of land and labor, and cost of acquiring mineral fertilizers. In short, the incentives for producing and using specific types of nutrient inputs are highly variable across the continent.

The physical and agroclimatic conditions in Sub-Saharan Africa are extremely diverse. Broad agro-ecological zones range from the semi-arid tropics, with around 400-800mm of rain per year, to humid highland regions that may average over 1,800mm of rain supporting two growing seasons. Soils are also quite distinct in texture, inherent soil physical, chemical, and biological health, potential for erosion and other forms of degradation. For example, crusting is a major problem in the semi-arid zone, aluminum toxicity in the humid lowlands, and erosion in the hilly highlands. In the more favorable zones, a wider range of organic based systems will be feasible, but they will also need to compete against a wider range of agricultural enterprises for land and labor. In the drier zones where growing plants becomes riskier and costlier, livestock assumes a more important role in the provision of organic nutrients.

Soils are also highly varied within small geographic areas. They maybe affected by physical features such as topography or historical land use and vegetation cover. Thus, it is quite common to find relatively fertile soils where deposition has taken place due to erosion. Soil variation may also occur across or within farms due to management patterns. For example, greater soil fertility status has been found among wealthier than poorer households in western Kenya (Shepherd and Soule, 1998) and in plots near homesteads (Prudencio, 1993).

Population densities vary noticeably within each of these zones, but generally, population pressure is highest in the more favorable agricultural zones. They are relatively lower in the semi-arid lands and minor portions of the humid lowlands (e.g. in forest margin areas) and subhumid zone (e.g. Zambia). They are highest in the highlands of East Africa, with densities of over 600/km^2 being very common. Densities of 250/km^2 or more are also found in some humid lowlands and sub-humid areas in West (e.g. Nigeria) and Southern Africa (e.g. Malawi). Such densities imply that average farmsizes among smallholder farmers will be 2 hectares or lower. Small farm sizes limit farmers' ability to find niches for the production of intermediate inputs for green manure or feed for livestock. Despite high population densities, the agricultural labor supply is not always plentiful in such areas, especially where school enrollment rates among children are high and non-farm income-earning opportunities are strong. Moreover, many very poor rural households are relatively labor scarce, exhibiting high shadow wage rates (Barrett and Clay forthcoming), limiting uptake of labor-using technologies, even among the poor in high population density areas.

Market infrastructure development is similarly varied across the zones, but is not fully functional or efficient in any of the zones. There are low densities of main trunk roads with feeder roads that are of low quality and often seasonally impassible. The more densely populated areas enjoy somewhat better transportation opportunities, piggy-backing on public transport vehicles and greater densities of market centers. Despite a general tendency towards liberalization of both input and output markets throughout the continent, in some cases government parastatals still play an important role (e.g. coffee in Kenya, maize in Malawi). Further, liberalization has yielded spatially heterogeneous and generally mixed price and market access incentive effects due to changing risk characteristics, limited inter-seasonal credit availability, and meager private storage or transport capacity (Yanggen et al. 1998, Barrett and Carter 1999, Reardon et al. 1999).

3. Organic nutrient management, integrated soil fertility management, and crop yields in SSA

The Integrated Soil Fertility Management (ISFM) paradigm acknowledges the need for both organic and mineral inputs to sustain crop production without compromising on environmental issues (Buresh et al., 1997; Vanlauwe et al., 2002). The paradigm further acknowledges that plants also require a conducive physical, biological, and chemical environment, apart from nutrients, to grow optimally. Besides these organic and mineral inputs, the soil organic matter pool, which reflects past soil management strategies, is another substantial source of nutrients. Each of these sources contributes to crop production and the provision of environmental services individually, but more interestingly, these resources can be hypothesized to interact with each other and generate added benefits in terms of extra crop yield, improved soil fertility status, and/or reduced losses of nutrients to the environment.

The earlier work on soil fertility management in SSA focused on the use of mineral inputs to sustain crop production. Numerous studies that have looked at crop responses to applied fertilizer report substantial increases in crop yield and financial returns (e.g. Yanggen et al., 1998; Snapp et al., 1999). National fertilizer recommendations exist for most countries, but actual application rates are nearly always much lower due to constraints of a socio-economic rather than a technical nature (see section 5). On the technical side, however, mineral inputs were further discredited due to the observed environmental degradation resulting from massive applications of fertilizers and pesticides in Asia and Latin America between the mid-1980's and early-1990's as a spin-off of the Green Revolution (Theng, 1991). As a result, soil fertility management strategies were refocused towards the use of organic amendments and considerable enthusiasm emerged around so-called "agro-ecological" approaches to agricultural development in the tropics (Uphoff 2001).

Among the most commonly used or promising organically based soil nutrient practices are: animal manure, compost, incorporation of crop residues, natural fallowing, improved fallows, relay or intercropping, and biomass transfer. These are briefly described in table 1 below. While we focus on soil nutrient management practices, there are a host of other management practices that are vitally important to overall soil fertility, including soil conservation techniques, weed management practices, and cropping strategies themselves.

Initially, organic resources were merely seen as sources of nutrients, mainly nitrogen (N), and a substantial amount of research was done on quantifying the availability N from organic resources as influenced by their resource quality and the physical environment (see Palm et al., 2001, for example). Various classes of organic resources were identified based on their short-term N supply, which in turn depends on nutrient acquisition methods, concentrations of nutrients in biomass, total biomass production, and decomposition characteristics (Vanlauwe and Sanginga, 1995; Vanlauwe et al., 1998). More recently, other contributions of organics have been emphasized in research, such as the provision of other macro and micro-nutrients, reduction of phosphorus sorption capacity, carbon/organic matter, reduction of soil borne pest and disease spectra in rotations, and improvement of soil moisture status. There are some key differences in the way that the organic systems contribute to soil fertility. Those systems that use nitrogen-fixing species are able to add nitrogen without withdrawing it from soils (either *in situ* or *ex situ*). Some can produce over 150 kg of nitrogen per hectare (e.g. a single season crotalaria fallow). Plant systems that are based on trees may further recycle deep nutrients (through roots) that would otherwise have been unavailable to annual crops. The different systems are not necessarily equally effective in providing nutrients. Organic sources will differ in terms of nutrient content, mineralization processes (in which the nutrients in the organic compounds can become available to the crop), and the provision of other soil fertility benefits (e.g. weed reduction). Aside from the organic source itself, management aspects can also affect the effectiveness of organics in increasing soil fertility. A key management distinction is the growing of legumes *in situ* (as opposed to transferring biomass from outside the plot) which can provide other benefits to crops through rotation affects (e.g. reducing the incidence of weed) and through water infiltration effects (from the root systems).

Despite these positive aspects, organic nutrient systems are not able to sufficiently replenish soils by themselves. First, concentrations of phosphorus and potassium are very low in organic manures. Second, the efficiency with which N and other nutrients can be used by crops can be low. Other problems related to the sole use of organic inputs are low and/or imbalanced nutrient content, unfavorable biomass quality, limited land for production of organic material, or high labor demand for transporting bulky materials (Palm et al., 1997).

It has been recently acknowledged that organic and mineral inputs cannot be substituted by one another and are both required for sustainable crop production (Buresh et al., 1997; Vanlauwe et al., 2002). This is due to (1) practical reasons – the amount of either fertilizer or organic resources alone would not be sufficient or organic resources were found unsuitable to alleviate certain constraints to crop growth, e.g., the lack of P in Nitisols with strong P sorption characteristics (Sanchez and Jama, 2002) and (2) the potential for added benefits created through positive interactions between organic and mineral inputs. Several attempts to quantify the size of added benefits and the mechanisms creating those have been made. Vanlauwe et al. (2002) reported that integration of maize stover increased the recovery of urea-N, most likely due to its temporary immobilization of urea-N. In a multilocational trial in West Africa, Vanlauwe et al. (2002) demonstrated added benefits from combined organic and mineral treatments through reduced moisture stress at critical growth phases of the crop. In a set of trials in sandy soils of Zimbabwe with various mixtures of cattle manure and ammonium nitrate, Nhamo (2001) observed added benefits ranging between 663 and 1188 kg maize grains per hectare. This synergy was attributed to the supply of cations contained in the manure.

Although the above list of observed positive interactions between organic and mineral inputs is not exhaustive, very often these inputs are also demonstrated to have only additive effects. But because of declining marginal increases from one single type of input, the additive effects are often superior in terms of overall yields and net returns, as shown by Bationo et al. (1998) for millet in Niger and Rommelse (2000) on maize in Kenya. Fortunately, negative interactions are hardly ever observed, indicating that even without clearly under standing the mechanisms underlying positive interactions, applying organic resources in combination with mineral inputs has negligible downside risk and considerable upside potential, thereby constituting an appropriate fertility management principle.

The ISFM paradigm has further broadened the scope for potential interventions in a number of ways. First, interactions between various crop growth factors were widened beyond nutrients. In Sahelian conditions, e.g., Zaongo et al., (1997) observed striking increases in water use efficiency for sorghum after application of fertilizer. Secondly, recognizing that soil fertility varies widely within a farm due to site-specific management by the farmer with drastic effects on crop yields, attempts are on-going to target resources, both of organic and mineral origin, to this within-farm variability in soil fertility status, rather than developing blanket recommendations. Bationo et al. (Unpublished data) showed a considerable improvement in P use efficiency from 47 to 79% when applying the P on a non-degraded homestead field rather than a degraded bush field. Vanlauwe et al. (Unpublished data) showed that N fertilizer use efficiency decreased from 45 to 30% when topsoil carbon contents increased from 0.3 to 0.8%. Thirdly, ISFM also highlights the need for improved germplasm. Improved crop germplasm does not only have a major role to play in improving nutrient acquisition but also in providing more organic inputs. Efforts have recently been made by various research centers to develop dual or multipurpose grain legume varieties (e.g. Sanginga et al., 2001).

In summary, there is considerable evidence demonstrating the important contributions of organic matter to agricultural crop yields. There is more limited, but still significant evidence attesting to the positive impacts of integrating organic and mineral nutrient sources in the short and long term. One interesting caveat is that nearly all research on ISFM has taken place on cereal crops. Yet, as we shall see in section 5, much fertilizer use by smallholders in Africa is steered towards more high value crops. The effects of organics and ISFM on non-cereals remain under-researched.

4. Actual nutrient management practices of African farmers

There are likewise several socio-economic sources of complementarity between organic and mineral inputs in soil fertility maintenance. Mineral fertilizer must be brought to the farm while organics can be home-grown, saving on transport costs and reducing uncertainties of market acquisition. The two approaches to soil fertility management require investment using different household resources, with fertilizer requiring financial capital and organics requiring labor and land (initial investment in livestock will require capital). The capital-intensive nature of fertilizer use is exacerbated by inflexible packaging arrangements creating a minimum $20 - $30 expenditure for a single bag. Several development projects and retailers sell fertilizer in smaller amounts, but farmers' lack of trust in shopkeepers seems to inhibit the growth of decentralized repackaging. Finally, in terms of quantities available, imported mineral fertilizers are in theory plentiful if the demand is there. On the other hand, production of organics is limited by available land and therefore supplying sufficient amounts for one's farm, let alone for sale in the market, can prove challenging.

Macro or meso level factors may impinge on the ability of communities to access certain types of nutrients. For example, fertilizer has been absent from retailers in Uganda until recently and is more readily available in peri-urban areas than in remote areas, very few cattle keepers are found in Malawi, and many types of green manures cannot grow effectively in drier zones. But it is the heterogeneity among households more than variation between agroecological zones that explains most of the observed differentiation in the use of different soil fertility practices. Significant uptake of integrated organic and mineral practices for improving soil fertility has occurred throughout SSA, in the highlands of East Africa (Murithi, 1998; Gebremedhin and Swinton, 2002; Place et al., 2002a; Clay et al., 2002), the humid lowland zone (Tarawali et al., 2002), the sub-humid zone (Mekuria and Waddington, 2002; Kristjanson et al., 2002; Peters, 2002), and the semi-arid areas (Freeman and Coe, 2002; Shapiro and Sanders, 2002; Kelly et al., 2002). Studies also show significant payoffs from the integration of mineral and organic sources of nutrients across different ecozones (Place et al., 2002a; Kelly et al., 2002; Shapiro and Sanders, 2002; Freeman and Coe, 2002; Peters, 2002; Mekuria and Waddington, 2002).

Several interrelated micro-level factors are at play in farmer input use patterns, including commercialization and access to land, labor, and capital. It is quite well documented that fertilizer use is strongly linked to commercialized production of cash crops (Kelly et al., 2002), ranging from parastatal run input-output supply programs to informal and opportunistic networks of peri-urban agriculture. There is some evidence to suggest in cash cropping systems organic inputs replace fertilizer when fertilizer supply becomes problematic (Bosma, *et al.*, 1996; Mortimore, 1998) or that the availability of mineral fertilizers for use on cash crops facilitates a broadened use of organic materials on food crops (Raynaut, 1997).

The relationship between commercialization and organic systems is also in general positive (Murithi, 1998; Kelly et al., 2002; Freeman and Coe, 2002), but there are obvious exceptions. Use of manure on cereal food crops is an old practice in the Sahel and southern Africa and continues today (Enyong et al, 1999; Williams, 1999; Ndlovu and Mugabe, 2002). Experimentation with new, plant-based, organic inputs often begins with their application on cereal crops, following traditional practices such as heaping or burning of familiar plant residues (Snapp et al., 1999). But animal manure is also commonly used on higher value commodities such as potato, coffee, and vegetables (Freeman and Coe, 2002; Shapiro and Sanders, 2002). And, as with manure, farmers have shifted promising innovations using new green organics systems (or integrations of organic and mineral fertilizers) onto higher value commodities such as vegetables (Place et al., 2002a). Furthermore, small farmers appear to consistently favor organics that serve as more than just a soil fertility amendment, offering food or animal feed that can be consumed or marketed as well, as with dual purpose legumes such as pigeon pea.

This pattern underscores that the positive yield returns described in the previous section can make the use of organics remunerative even in semi-subsistence systems, including places where purchased fertilizers remain unattractive. This difference, the propensity for using organics to increase production in high-value systems and farmers' preference for dual-purpose varieties over those that serve as fertility-enhancing inputs only, highlight the value of cash liquidity in areas plagued by a dearth of inter-seasonal credit. Those who earn cash from crop sales, or can avoid spending cash on input purchases, can often afford to hire labor or to purchase food and thereby dedicate their labor to input production on their own farm instead of having to hire out their labor in order to earn wages. But when the labor demands of the low external input (LEI) technology are substantial, as in many biomass transfer systems or other LEI technologies, the foregone wage earnings can impede adoption among poorer farmers (Reardon et al. 1999, Moser and Barrett 2002).

Land availability commonly constrains use of organic inputs produced on farm, like improved fallows (Place et al., 2002a). On the other hand it is not a major factor in biomass transfer systems, which are often focused on small plots of high value crops. The evidence on the effect of labor availability on adoption of organic inputs is mixed. While additional labor effort is often identified by farmers, they commonly find ways to reduce labor burdens to fit their needs through adaptation of extended technologies. For example, intercropping of pigeon pea with maize in Malawi saves labor (and land) compared to a sequential system (Waddington, 1999). Farmers in Western Kenya are also opting to use local plant species (such as *Tithonia* or *Vernonia*) identified as good nutrient sources as additions to existing composting systems, which use labor in small increments rather than as part of cut-and-carry systems which would demand major labor inputs at the time of crop planting (Misiko and Ramisch, unpublished data).

A key motivation for the promotion of organic nutrient systems is that by requiring little capital, they might reach the poor better than commercially distributed fertilizer. This is critical, because many studies have found that the poor are unable to use mineral fertilizers and the consequences on soil fertility and farm incomes are enormous (Soule and Shepherd, 2000). This largely seems not to be true in the case of animal manure because incomes tend to be highly positively related to livestock ownership. Manure use therefore appears to increase with a household's wealth (Mekuria and Waddington, 2002). But poorer households are using agroforestry-based nutrient systems and compost in Western Kenya at the same proportion as wealthier ones (Place et al., 2002a). Moreover, participatory methods are involving the poor much more in technology design.

Will the use of organics encourage greater use of mineral fertilizers?[1] A recent study of agroforestry improved fallow and biomass transfer systems in Western Kenya found that the systems were being used by 30 – 45 percent of those households who were not using fertilizer or manure (Place et al., 2002c). However, the use of agroforestry has not yet spurred an increase in the use of fertilizer. On the other hand, Abdoulaye and Lowenberg-DeBoer (2000) analyze data from Niger to show that patterns of intensification exhibit a pattern of graduation from manure to mineral fertilizer use. Expansion of options is good for smallholders. However, there remain information gaps as to how much the different options are being perceived as complements or substitutes by farmers.

5. Implications of organic nutrient systems on input markets

Markets depend fundamentally on there being positive net returns to moving goods across space or time, through transport and storage, respectively. The development of markets (formal or informal) for organic

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[1] This relationship is not at all straightforward because proceeds from better harvests will normally be spent on other items before the time when fertilizer is needed for the next season.

inputs in Africa, as throughout the world, has been shaped and constrained by the extreme variability in the supply of organic resources and their relative 'bulkiness' (low nutrient value per unit mass). These factors conspire to limit trade in organic inputs, leading to extremely localised patterns of use.

The supply of organic resources that are potentially important contributors to agriculture – manure, crop residues, and other plant biomass – is both seasonally and spatially variable. Spatial variability can be observed as gradients of input use at the farm scale, inter-household variability based on differential resource endowments, and variability at the landscape and higher levels due to agro-climatic differences. Seasonal variability affects the abundance of key materials: crop residues are available in vast quantities only at harvest or as thinnings before then, manure is more abundant during rainy seasons than in dry ones but more likely to be dispersed by grazing across the landscape. Temporal variability is also seen in the quality of materials. The nitrogen content, in particular, of manure or harvested organic materials declines rapidly with the passage of time, as does the overall nutrient value of young plant materials like leaves if they are allowed to mature or senesce. Inter-seasonal storage of organic soil nutrient amendments is therefore impractical.

The second factor, bulkiness, is a key constraint on the transport of organic materials over any significant distance for use as inputs. The much observed 'ring management' of many Sahelian farming systems (cf. Prudencio, 1993; Ruthenberg, 1980) results from the concentration of inputs on fields declining with increasing distance from their source (typically the homestead). Comparing yield benefits from manure application against the labor involved in transporting it, Schleich (1986) found that for a community in Côte d'Ivoire, ox carts were profitable up to a distance of 1 km, whereas transport on foot was not profitable at any distance. Since animal powered transport can increase the efficiency of labor-intensive transport activities to the point of profitability, dynamic community-level markets for the exchange of draft power have been reported for transporting manure (Mazzucato and Niemeijer, 2001 in Burkina Faso; Ramisch, 1999 in Mali; Tiffen *et al.*, 1994 in Kenya; Sumberg and Gilbert, 1992 in the Gambia).

Because transportation is an important limit, there is a strong incentive to produce organic inputs *in situ* (such as companion planting of legumes with cereal crops or as improved fallows in rotation with them). An animal based analogue is the corralling of animals on fields in the dry season, which exchanges crop residues for manure. Throughout much of West Africa, the manure of large semi-sedentary and transhumant herds is a key resource for settled farmers (Landais and Lhoste, 1990; Bonnet, 1988; McIntire and Gryseels, 1987; Powell and Coulibaly, 1995), and such manure is often the catalyst for inserting pastoralists into the exchange networks of a settled community (Ramisch, 1999; Guillard, 1993; Dugué, 1987; Lachaux, 1982). Where markets can valorise increased crop production, exchanges of 'surplus' manure or compost between settled farmers are also common, either for cash (Tiffen *et al.*, 1994) or labor for other activities (Ramisch, 1999; Guillard, 1993).

High labor requirements for collection, transportation, and application of organic inputs are an important limiting factor for market participation. Where local labor markets and credit are incomplete, a household's capacity to use organic inputs depends primarily on the availability of household or reciprocal labor (Ahmed et. al, 1997; Barrett et. al., 2002). This has implications for labor allocation decisions that may not be consistent with households' income diversification strategies. The low quality of manure being used by many farmers under traditional management systems results in low concentration of plant nutrients (especially nitrogen and phosphorous) and correspondingly low returns to farm labor (Probert, n.d.). Under these circumstances households may seek to free farm labor to pursue off-farm activities that provide a higher return or are less risky. HIV/AIDS has also reduced labor availability for farm work in many countries in eastern and southern Africa These households are likely to prioritise labor saving technologies even in perceived labor surplus areas. Nonetheless, surprisingly little is known about how returns to integrated soil nutrient management practices compare with alternative investments off-farm.

The problem lies not just in markets for soil amendments themselves, but also in the materials for *in situ* production of organic inputs. Farmer willingness to pay for germplasm for green manure is low because of free distributions by projects, high quantities demanded, and an ability to harvest and reuse seed for most green manure plants. Where intensification of leguminous grains is linked to market development farmers have shown greater willingness to invest in improved seeds (Jones et. al., 2002). The challenge here lies in identifying the right varieties that have the best potential for fixing nitrogen while at the same time meeting preferred market requirements for the food product beyond soil fertility improvement. The proliferation of markets for *Mucuna* seeds in West Africa, for example, was related to its perceived ability to suppress the noxious grass *Imperata*. Within 2-3 years this weed was controlled and *Mucuna* no longer marketed (Houndekon *et al.*, 1998). Species with multiple benefits, such as dual-purpose soybeans or cowpeas are more likely to be adopted than those purely for soil improvement. Social networks play an important role in facilitating the reallocation of slack resources (Mazzucato and Niemeijer, 2001). The anecdotal evidence that exists for the development of seed distribution markets for legume cover crops suggests that social networks are paramount in spreading both information and the small amounts of seed that become periodically available for members outside the group (Misiko, 2000).

6. Summary and ways forward to enhance the contribution of integrate soil fertility management

Integrated soil fertility management practices are thriving in agricultural research and development projects, as the use of organic inputs increases, both on a stand-alone basis and in conjunction with mineral fertilizers. Much of this initiative is due to farmer innovation and adaptation, often in response to macroeconomic and sectoral reforms that have driven up real fertilizer prices throughout the continent. Organic systems have been found to complement fertilizers in many ways, both in a biophysical sense (enhancing soil fertility beyond nutrients alone) and in a socio-economic sense (requiring different types of household resources). Some organic systems are performing well on their own and in integrated systems, as measured by yields and profits. Like mineral fertilizer, there appears to be more interest in, and impact from, the use of organics and integrated systems on higher value crops. Because of their low cash requirements, some organic-based systems are reaching poorer households that otherwise are scarcely using any fertilizer.

But there are limits to the amounts of organics that can be produced on-farm, particularly where labor constraints bind. There remains insufficient evidence as to whether increased use or organic inputs is spurring increased overall use of nutrient inputs. While biophysical research in integrated soil fertility management is progressing rapidly, more research is needed on farmers' practices, including their innovations and integration of individual components. There is also an urgent need to extend both bodies of research to higher value crops and whole farm analyses.

Markets for organic biomass are limited mainly due to the inherent characteristic of relatively low quality of nutrients per weight resulting in bulkiness. Markets have developed for animal manure, especially quasi-contractual arrangements between owners of free grazing cattle and stover owners. Markets for green manure do not exist to any significant degree. Markets for green manure germplasm have developed in response to demand from projects and from farmers when the plant yields feed or food product in addition to soil nutrient replenishment.

In order to ultimately contribute to increased productivity through improved soil fertility management, a few steps can be highlighted. First, there is still need to develop more attractive options, components and integrated strategies for small farmers of which improved germplasm is an integral part. This requires tighter linkage and feedback between strategic and adaptive research activities. Farmers are moving quickly in experimentation and the researcher community must be more active in monitoring this work. This will require more partnerships among farmers, extension, development projects, and researchers to bring wider development efforts into the knowledge base of researcher.

Second, because ISFM practices are knowledge intensive, a major challenge is to identify scaling up processes that are both effective and not too costly in terms of information provision and technical support. It will be especially challenging to overcome the many bottlenecks of information flow across different organizations, from organizations to communities, between communities, and between farmers within communities. There is a need to develop incentive systems that reward improved flows of information. Rewards to communities for their efforts similar to the Landcare system in the Philippines or the Presidential award in Kenya are worth exploring, as are ways of utilizing existing rural collective action (e.g. community-based organizations) to facilitate information flow.

Third, there must be major efforts to make agricultural commercialization more attractive to small farmers. Low rates of market participation are leading correlates of both poverty and the absence of sustainable agricultural intensification through increased investment in the land (Barrett and Carter 1999, Reardon et al. 1999). Increasing commercialization requires improving access to input markets, including for working capital (e.g., credit, savings) needed to purchase mineral fertilizer, organic inputs and seed and to hire labor, perhaps especially for women, who are key soil fertility managers in much of the continent. This is relatively easier in favorable agricultural zones where investment in market infrastructure can have a big impact. Indeed private, commercial interests sometimes undertake such investment voluntarily in support of lucrative contract farming schemes. Stimulating greater market participation is trickier in drier areas, although research from South Asia suggests that the marginal returns, in terms of both poverty reduction and production value, are highest for road infrastructure investments in low potential rainfed areas (Hazell and Fan 2001). Roads are important, but the organization of marketing and finance demand attention as well, building on local self-help groups to help resolve coordination and contract enforcement problems bedeviling much commerce in rural Africa today.

Rapid growth in experimentation with organic soil inputs has fuelled the emergence of an extremely promising integrated soil fertility management paradigm that is just beginning to be evaluated carefully. A wide variety of studies report widespread experimentation with ISFM across all agroecological zones in Africa, including by many farmers who had not been using mineral fertilizers. Nonetheless, problems of market access, and household-level availability of land, labor and working capital continue to limit the extent of adoption of ISFM among poorer small farmers. One finds pockets of active and effective users surrounded by vast areas of non-use.

Much remains to be done, both in terms of research and development practice, to establish how best to employ the emergent ISFM paradigm to overcome or increase Africa's miniscule rates of mineral fertilizer application and stimulate agricultural productivity growth. The task is made all the more pressing by economic policy reforms that have caused a sharp drop in fertilizer use by small farmers in many areas. The core challenges to scaling up limited successes with ISFM to date appear threefold: improving integration between strategic and adaptive research, accelerating and expanding the flow of information among farmers, and increasing agricultural commercialization through improved market access, especially in lower potential rainfed regions.

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Table 1: Description of Main Organic Soil Fertility Practices in Sub-Saharan Africa

Organic Practice	Description
Animal manure	The spread of solid and liquid excrement from animals, mainly cattle. Intensified livestock production systems involve the collection of manure in stalls or pens, while the more extensive systems involve direct deposition of manure by grazing animals.
Compost	The collection and distribution of a range of organic compounds that may include soil, animal waste, plant material, food waste, and even doses of mineral fertilizers. Prior to application of compost onto the field, there is a period of incubation to decompose materials.
Crop residues	The in situ cutting, chopping, and incorporation of crop residues into the soil. This operation is often done at the time of land preparation for the following season.
Natural fallow	Withdrawal of land preparation or cultivation for a period of time to permit natural vegetation to grow on the plot. The breaking of the crop cycle and lead to regeneration and the fallows can also recycle nutrients.
Improved fallow	The purposeful planting of a woody or herbaceous plant to grow on a plot for a period of time. In addition to benefits of natural fallows, improved fallows can achieve equal impacts of natural fallows in shorter time periods because of purposeful selection of plants, such as those that fix atmospheric nitrogen.
Intercropping systems	Nutrient sources are integrated with crops in both time and space. The organic source may be a permanent feature on the plot such as with alley farming or scattered trees or may also be annual legumes. Intercrops are normally carefully planted, but trees in certain parkland systems (e.g. *Faidherbia albida*) are naturally growing.
Relay systems	Relay systems are similar in sharing space with the crop, but the organic source is planted at a different time than the crop.
Biomass transfer	The transport and application of green organic material from its ex situ site to the cropping area. The organic source may be purposefully grown or growing naturally.

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Finding common ground for social and natural science in an interdisciplinary research organisation – the TSBF experience

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Abstract: Continuing dialogue between the natural and social sciences means that the conception of "development", and of integrated natural resource management (INRM) in particular, continues a healthy evolution from largely discipline-based approaches to more integrative, holistic ones. Reflecting a microcosm of this evolution, the Tropical Soil Biology and Fertility (TSBF) Institute of CIAT is today dedicated to integrated soil fertility management and the empowerment of farmers through participatory technology development. Yet its origin in 1984 was as a body devoted to researching the role of soil biology in maintaining soil fertility, to combat declining per capita food production and environmental degradation.

This paper examines the changing theoretical and methodological approaches of integrating social science into TSBF's research activities over the past decade, and identifies strategic lessons relevant to INRM research. The interdisciplinary "experiment" of TSBF has steadily taken shape as a shared language of understanding integrated soil fertility management. While individual disciplines still retain preferred modes of conducting fieldwork (i.e.: participant observation and community-based learning for "social" research, replicated trial plots for the "biological" research) a more "balanced" integration of these modes is evolving around activities of mutual interest and importance, such as those relating to decision support for farmers using organic resources. Since TSBF is working constantly through partnerships with national research and extension services, it has an important role in stimulating the growth of common bodies of knowledge and practice at the interface between research, extension, and farming. To do so requires strong champions for interdisciplinary, collaborative learning from both natural and social science backgrounds, the commitment of time and resources, and patience.

Rationale: As part of a CG-wide review, papers were invited which analyze the contribution of social research (sociology, anthropology, geography, political science, psychology) to research process, results, outcomes and development impact of agricultural or natural resource management research. Papers should assess the extent to which social research has influenced the relevance of research outcomes for the poor. Preference will be given to papers that analyze experience over time with social research and its impact in an organization such as a CGIAR Center, National Agricultural Research Institute or NGO, as distinct from a project. Topics to address include:

1. Introduction: brief overview of the history of social research in the institution that identifies main phases and trends over time in number and type of staff and resources involved and their main objectives.
2. What have been the effects of social research done by the institution on research and innovation processes : e.g. on problem identification, research priorities, client or target group identification, methodologies, on-farm approaches, technology design, criteria for successful results, scaling up, evaluation, impact assessment etc. How and why has this changed in relation to the main phases and trends in use of social research over time identified in (1) above ?
3. How has social research done by the institution been incorporated into the organization, its work culture, team composition, policies and procedures. Have synergies been achieved by combining social research with other disciplines? Why or why not?
4. Are there any effects of social research on results achieved by the institution, on adoption and use of its research results by client groups, outcomes of use for clients, and development impact associated with the institution's research. If there is no evidence to enable you to address this question, why is this ?

5. Has social research had any influence on relevance to the poor of the institution's research? Why or why not? If there is no evidence to enable you to address this question, why is this ?
6. Conclusion: summarize the critical success and/or failure factors that have affected the use of social research by the institution and lessons learned.

1. Introduction

The Tropical Soil Biology and Fertility (TSBF) Programme (now Institute) was created in 1984 under the patronage of the Man and Biosphere programme of UNESCO and recently incorporated into the Future Harvest system of food and environment research centres as a research Institute of the Centro Internacional de Agricultura Tropical (CIAT). As an international research body, the underlying justification of TSBF's work has been that "the fertility of tropical soils is controlled by biological processes and can be managed by the manipulation of these processes" (Woomer and Swift, 1994).

Being an organisation with an explicitly biological and ecological mandate and origin, TSBF has nonetheless sought social science input into its research program since 1992. It has always been a small team (never more than six internationally recruited scientists) and therefore much of TSBF's considerable output has been generated through collaboration with partner organisations (both national and international), with special focus on sub-Saharan Africa. The decision to develop and maintain a core competency at the interface of social and natural sciences at TSBF since 1992, rather than looking for such competency from partners, is therefore significant. A decade after the creation of the Resource Integration Officer (since renamed Social Science Officer) position, it is worth re-evaluating the effects and effectiveness of this decision.

This paper examines TSBF's historical record as a "laboratory" for developing meaningful interdisciplinary dialogue and collaboration, and asks whether what has emerged has been "social soil science" or merely "soiled social science". To illustrate some of the tensions inherent in interdisciplinary undertakings, examples of theoretical and methodological evolution are drawn from "grey" project literature, personal commentary, and publications. The strategic lessons learned from this particular organisation reflect in microcosm the much broader debates about the potential for "rigorous" science under competing disciplinary approaches to integrated natural resource management (INRM). They also address the assumption that developing a common institutional culture and language within INRM falls more to social scientist "newcomers" than to biological or natural scientists.

2. Theoretical shifts

The smallness of TSBF when contrasted with the larger international research centres has obliged an inherent recognition that the organisation cannot do all things in all places. As a result, strategic decisions about which research themes and methods to pursue become all the more important. "Smallness" has also meant that individual personalities and disciplinary backgrounds have had a much more direct impact on the organisational research agenda and that agendas can change with less institutional inertia than would be the case in a larger centre. On the down side, the institution has been very vulnerable to changes in core personnel (especially the gaps that occur when posts are changing hands) and frequently science has taken a back seat to mere matters of survival.

The development of a TSBF research agenda that looked beyond the soil to the people cultivating it has moved from descriptive, characterisations of farming systems to more strategic study of social differentiation, power, and networks as they relate to soil fertility management innovation. An interest in dissemination has broadened into investigation of social dynamics, knowledge, and farm-level decision-making. There has also been a tradition of self-reflection, examining the consistency and coherence of TSBF's stated goals, methods, and actual practice, as well as the extent to which grassroots action conforms to its depiction to outsiders. As such, social science practice has developed quite healthily over the ten years 1992-2002, driven significantly by the following factors:

a) The <u>disciplinary background</u> of the Social Science Officer (and to a lesser extent, that of field staff). Three people have held this position – Simon Carter (1992-1997, Geographer), Patrick Sikana (1998-2000, Anthropologist), Joshua Ramisch (2001-present, Human Ecologist) – and each has had preferred research topics and interests. In addition, Eve Crowley (1994-1996, Anthropologist) worked with TSBF on a Rockefeller Social Sciences Fellowship; a position shared half time with ICRAF.

b) The <u>demand for "socio-economic" understanding</u> of processes being studied by other TSBF staff and collaborators.
c) The natural <u>evolution of projects</u> from inception to later stages. This organic growth has typically moved from characterisation using very descriptive studies to more explanatory work building on existing practices through to development of longer-term interactive learning activities.
d) <u>Evolving social science debates</u> concerning knowledge, power, and participation. The co-supervision of MSc and MA students from local universities has been an especially useful vehicle for maintaining contact with these debates.
e) Responding to <u>donor agendas</u>, including but not limited to perceived needs for research results readily useful to farmers, a clearer understanding of agrarian change and its links to changes in soil fertility, livelihoods analysis, impact assessment, and identifying the most effective ways of "scaling up" organisational successes.

<u>2.1. Demand driven – but by whom?</u>

There has always been a tension between the research agendas demanded from *within* TSBF by social scientists (i.e.: disciplinary interests, evolving projects and debates) and those expected from *outside* (i.e.: from other TSBF staff, partners, donors). This tension results from different research paradigms and differing ideas about the role of research in relation to social change. From the natural science perspective, the key contribution of social science to INRM often appears to be identifying and understanding the social factors that limit "adoption" or the "appropriateness" of given technologies. Other socio-cultural phenomena, such as "policy" might be acknowledged as important to the fate of different innovations, but most teams (even multi-disciplinary ones) lack the capacity to generate relevant policy-related questions, experiments or interventions. In other words, when the organisation is researching natural resource problems, the natural-social science dialogue has most often begun with identifying "black boxes" of external, *social* forces that need illumination, rather than defining truly *interdisciplinary* questions about how research (including technical research) can support positive change in rural societies.

This tension is reflected clearest in the history of the social science position itself, which is discussed at length in the next section. Created in 1992, the post was originally charged with "Resource Integration". This step was perceived as a natural evolution for TSBF, which always held an ecological, systems-oriented approach to thinking. Although TSBF's strength remained at the plot level, the diversity of forces impinging on the plot draws attention naturally towards a hierarchical systemic analysis (Scholes *et al.*, 1994).

The Resource Integration Officer was therefore initially charged with "developing a model for integrating biophysical and socio-economic determinants of soil fertility for small-scale farms" (Swift *et al.*, 1994). Under this rubric, social factors were expected to be integrated into holistic models as additional explanatory variables. Once key, perhaps universal variables were identified, these could then be added to a "minimum set" of characterisation data collected for TSBF sites (cf. Anderson and Ingram, 1993). However, the main contributions to the TSBF programme remained in terms of site selection, selection of themes for process research, and client group selection, with much less emphasis on experimentation, or monitoring and evaluation (Crowley, 1995).

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2.2. Historical evolution

2.2.1. Carter (1992-1997)

The first incumbent in this post was a geographer, Simon Carter, with a background in both social and natural scientific traditions. Recognising the need to start from where TSBF "was at", but also charged with the task of helping to make the program's research more relevant to farmers, he began to work at the intersection between these two positions, and to generate information about how soil fertility was managed. Everyone in the programme agreed that it was important to know more about resource availability and use, and to begin to think about the relationships between research on soil fertility management and a better understanding of social and environmental change within African farming systems.

Understanding spatial variability in soil management was also a common concern to the programme, with practical implications at two different scales. Understanding the importance of spatial variability at plot and landscape scales, and how farmers dealt with these, had clear practical implications for research on-farm and in communities, such as the questions research should address, involving farmers, and designing experiments. Secondly, given that a high priority for TSBF was the development of its African network (AFNET), identifying key regional differences in soil fertility management strategies could be key to developing AFNET. As a result a range of work was undertaken including development of simple GIS databases for East Africa, a more detailed one for Western Kenya, detailed formal survey work in Western Kenya, participatory characterisation of farmers' recognition and management of farm and landscape-level management of soil variability in Kenya and Zimbabwe.

Carter (from 1994 with support from Eve Crowley) sought to align research at TSBF with on-going debates on agrarian change in order to broaden the conceptual base underpinning many of the assumptions about the potential contributions of ecological research on soil fertility management to rural development in Eastern and Southern Africa. Hypotheses generated from the literature drove much of the data collection efforts undertaken from 1993-1996 (eg. Crowley and Carter, 2000). In addition, efforts were made to expose AFNET members in Kenya and Zimbabwe to a range of on-farm research methodologies and tools and approaches that could, over time, facilitate inter-disciplinary exchange (Carter et al, 1992; Crowley & Carter, 1996). This work culminated in a four-country project funded by the EU from 1995-1998 (Carter & Riley, 1998).

The modus operandi that evolved within TSBF between 1992-1996 had important methodological implications, however, for the research undertaken by the Resource Integration Officer, and later the Social Science Fellow. The pressure was on them to demonstrate, through quantitative means, the validity of social science perspectives and the fallacies underlying some of the assumptions of colleagues, as well as to collect quantitative data that would be of use for biological and economic modelling (little use was made of the additional quantitative survey data that was collected on behalf of other colleagues, who were simply too busy with other projects and priorities to explore the data). With hindsight it was probably a strategic error to agree to conduct an extensive formal survey in Western Kenya. A lot of time and labour was spent generating, collating, cleaning and exploring the data, and insufficient priority was given to interdisciplinary analysis, writing-up and dissemination of the results. Difficulties in collaboration, the departure of the Social Sciences Fellow, and increasing demands from other projects undermined the considerable investment the programme had made in this work, although the long-term worth of the dataset is undoubtedly high. On a more basic note, insufficient priority was given in the early years to simply learning to communicate more effectively across disciplines.

Recognising that the unique contribution of the Resource Integration Officer to TSBF's overall research strategy was its attention to social questions, the position was renamed Social Science Officer in 1997. By this time it was recognised that the contribution of the post had had moved beyond collection of an enlarged "minimum set" and creating a more open "sequence" or menu of methods that would be useful for "defining the resource bases and management strategies of different socio-economic groups" (Carter and Crowley, 1995). Changes in personnel during 1996-7 had opened new opportunities for collaboration, and work moved into its strongest experimental phase, including researcher-managed experiments in conjunction with ICRAF, researcher-managed work under the EU project, and farmer participatory research begun in 1996. In 1997 a project was developed to support some of this on-farm experimental work. Significantly, it also included support for two masters students to look at how farmers in Western Kenya gained access to and shared knowledge about soil fertility management. This small step paved the way for a significant shift in focus over the next few years.

2.2.2. Sikana (1998-2000)

The brief tenure of Patrick Sikana brought the newly renamed Social Science Officer position towards much more autonomy on purely "social" research topics than had previously been the case. As a social anthropologist with farming system research experience in southern Africa, he prioritised deepening TSBF's understanding of farmers' local soil ecological knowledge and the rationales behind their existing soil management practices. This period also initiated critical investigations of how social networks aid and hinder the functioning of integrated soil fertility management (ISFM) research projects and the dissemination of ISFM knowledge.

However, there was a significant lag time of nine months between Carter's departure and Sikana's arrival, which would have implications on the ground (discussed in methodological changes below). Furthermore, Sikana had been in the post slightly over a year, and just begun organising new projects for the Social Science Office when he was killed in the crash of a Kenya Airways flight from Abidjan in January 2000. His death devastated the small organisation at a time when its future was also being shaken by financial uncertainty.

Indeed, the issue of continuity of personnel has had major impacts on developing an interdisciplinary and social science research agenda, at least in the short to medium term. Not only has TSBF seen significant turnover of personnel since 1992, but so has AFNET. The retrenchment of public sector employees, as part of structural adjustment or other "reform" programmes, has gutted national research bodies and extension services. The relatively low numbers of social scientists present in national systems must also been see in the light of the stark fact that they tend to be much more attractive to donors and thus more likely to move on from low paid national positions. Social scientists trained in participatory methods are also much less likely to return to agricultural research jobs when conservation and health present more prominent and well-funded fields. Finally, staff turnover in African organisations has been exacerbated by sudden deaths like Patrick's, attributable to disease, accidents, and general insecurity.

The AfNet membership is still overwhelmingly natural scientists (over 150 soil scientists, biologists, agronomists) with social science represented only by six (socio-) economists. While there is a general appreciation that "social science" is important to the network, there is still great unfamiliarity with what can really be offered or understood. The emphasis remains on economic information about the "profitability" or "adoptability" of known technologies, with no expertise or experience in applying strategic, interdisciplinary research questions at the interface of human-environment interactions to soil fertility management. AFNET could have made it a higher priority to try to attract more social scientists, but soil and agricultural scientists need to be trained to recognise where social science can make their lives easier. This has to happen at university and in special training courses, and (rather like gender mainstreaming) has to have the soil and agricultural scientists in TSBF as its champions, not just the social scientists. Host institutions have also to provide the space for scientists to engage in interdisciplinary research. Unfortunately, while recognised by the various AfNet coordinators, this has tended to be subsumed, and therefore obscured, within the larger problem (true within AFNET as within the CG system more generally) of declining numbers of soil scientists faced with increasing obligations and expectations.

The lack of "champions" for social science research within TSBF can also be seen in the example of Ritu Verma, an IDRC-funded MA student who worked with TSBF in Western Kenya from October 1997 to April 1998. Her research comprehensively examined gender and agricultural practice but without a strong link to the core of TSBF was never meaningfully integrated into other projects. Ironically, her book “Gender, Land, and Livelihoods in East Africa: Through Farmers’ Eyes” (Verma, 2001) is the most extensive TSBF text produced by social science research but presents its arguments in such detail that it has been difficult to absorb or disseminate, making it a testimony to missed opportunities.

2.2.3. Ramisch (2001- present)

One of the main objectives since the arrival of Joshua Ramisch in early 2001 has been enhancing the “institutionalisation” of the social science research agenda. This search for greater continuity within the research agenda has been assisted by the recruitment of two full time research assistants (a socio-economist based in Maseno, and anthropologist based in Nairobi), as well as broadened efforts at building a social science “constituency” within AfNet. Core activities of the office have retained an anthropological focus, including research on indigenous soil ecological knowledge, farmer decision-making, understanding innovation processes, and the role of social differentiation in ISFM practices

Staff turnover in 2001 also gave TSBF a chance at a relatively clean slate. The AFNET coordinator position was filled by Andre Bationo and Bernard Vanlauwe became the ISFM Officer at roughly the same time as Ramisch arrived. While there has been a risk of losing institutional memory through this process, the simultaneous arrival of so many new staff has facilitated team building, new collaborative activities, and presented opportunities for cross-disciplinary learning. Evidence of this interdisciplinary thinking has emerged clearly in presentations and papers written by core TSBF staff (e.g. Bellagio, Centres Week, and INRM presentations 2001, 2002; unpublished), as well as increasing numbers of interdisciplinary activities on the ground in Kenya, Uganda, and Zimbabwe.

The strategic alliance in 2001 with the Centro Internacional de Agricultura Tropical (CIAT) has helped give TSBF greater financial security and a higher profile. It also presents opportunities to link the Institute to a broader interdisciplinary community and to draw on the expertise of CIAT’s long-established social research programmes. While the transaction costs of inter-continental collaboration are high, crosscutting endeavours within TSBF-CIAT have taken place around the Bellagio meeting in 2002, the training of an Argentinean in NUTMON methods in Ethiopia, and joint supervision of an M.Sc. student in Western Kenya.

However, the 8th AFNET meeting held in Arusha in May 2001, also clearly demonstrated that amongst partners TSBF is still perceived essentially as a biology-based organisation with minimal social science input. Active recruiting of social scientists has begun through networking and proposal development, but has been complicated by the rapid expansion of AFNET in the past two years. The massive influx of new members and the expansion of activity into West Africa have simultaneously increased the potential demand for INRM input and diluted the few interdisciplinary voices present within the network. The AFNET mandate of increasing the use of “integrated” approaches frequently takes a back seat to its more “traditional” and familiar mandate of increasing support of biological approaches to partner institutes through curriculum development and networked experiments. The role of social science within AFNET remains an unresolved problem, acknowledged as important (for “integrated” resource management, for greater “adoption”, and ultimately donor approval of soil fertility management topics (Bationo, forthcoming)) but not backed by resources or strong champions within the network.

A final point to note is that all of the social scientists who have worked at TSBF have been relatively young and in the early stages of their careers, whereas the biological scientists have generally been more senior. The onus has been on the social scientists to communicate novel ideas in terms their colleagues could understand or accept; this was relatively easy with concepts such as spatial variability, but much harder with feminist political ecology. Furthermore, in the past, strong personalities or opinions have tended to block communication between individuals and to limit interactions within the team. The new team that came together in early 2001 has begun to overcome some of these historical difficulties, further stimulated by meetings held in conjunction with the union with CIAT and the formation of the strategic Alliance for ISFM between CIAT, TSBF, and ICRAF. However, without a more senior social scientist or generalist present to mentor or to mediate communication, interdisciplinarity will always be a challenge.

3. Methodological shifts

The most fundamental evolution has been from largely descriptive, empirical work towards developing more theory-driven, strategic research and the broader use of participatory approaches. At the same time, there has been a search for the optimal degrees of participation relating to the "fieldwork" aspects – which actors, doing which tasks, using which methods. This search has highlighted some of the still extant divides between the rhetoric of research aims and the realities of operational daily practice, as well as tensions that exist between different models of the role of research in stimulating change. Examples are drawn from among the longest-running TSBF projects.

3.1. "Research" or "action research"?

The development of social science at TSBF has been implicitly predicated on two very different models of how change is brought about in rural communities and what role outsiders and scientists can play in that process. The more conventional approach suggests that a "good technology sells itself" and that working with communities merely requires that the "best bet options" are made available to the "categories of farmers" who are likely to benefit from them. In this model, which is still widely held by many natural scientists including TSBF partners, a "research" organisation has too few resources and no comparative advantage in doing dissemination, and is better placed to research and evaluate the dissemination and technology promotion activities carried out by partners (local NGO's or national agricultural bodies). The alternate approach argues that understanding local processes of innovation, resource distribution, resource allocation decisions, and information transfer is essential to developing technologies relevant to their users' conditions. Integral to this second approach is the development of meaningful communication and learning across disciplinary boundaries – something that TSBF has attempted to do repeatedly, but which still remains problematic.

As TSBF and its partners became more versed in participatory methods, tension has developed between these models. The desire for more "development" oriented activity has been highlighted in the redesigning of the "Resource Integration" theme of TSBF in 2000 into the new Focus 1, demonstratively titled "Empowering Farmers", into which all the other bio-physical Foci's arrows flow. It may also have been further accentuated by the recruitment in the late 1990s of TSBF field staff for Kenya with NGO backgrounds in action research. The argument has been that without actively engaging in dissemination and community organisation the phenomena of interest to research (knowledge flows, further innovation and adaptation, etc.) will be too scarce to be viable or observable. Indeed, these staff members have found it difficult to define or implement "research" as an independent activity, devoid of extension or development components.

In reality, most partner organisations have lacked the resources (personnel, transport, and operating funds) to carry out such work, and indeed have often turned to TSBF for material or logistical support. The decision to devolve more of the research, experimentation, and dissemination activities to the host communities, therefore, is not so much ideologically driven as pragmatic. The increasing use of farmer-designed and farmer-run experiments, farmer-to-farmer training, and group-based activities has effectively begun to address the desire for more "action" oriented work while providing social processes worthy of investigation. What has emerged in the project areas of Western Kenya (where TSBF and local groups have had a reasonably long, 5-8 year history of contact) are prolonged, one-to-one relationships between scientists and farmers. Interactive, two-way learning, through community-based interactive sessions and farmer-based demonstrations, has been enhanced by researchers, and is widely conducted in local dialects. The ongoing challenge, however, has been finding optimal roles for researcher, extensionist, and farmer participation under these continuing conditions of resource constraint.

3.2. Collaboration and "participation"

Under the prevailing orthodoxy of participation, it is difficult to find projects that do not describe themselves as using and embracing "participatory" methods, to the extent that the term invites dismissal or covert cynicism (cf. Cooke and Kothari, 2001). These methods are usually assumed to apply only to relationships between researcher / extensionist and "client", where they are used to "level" the power relationships between actors. Yet in the TSBF context, where planning and implementation of activities is explicitly done in partnership with national research and extension institutions, participatory methods of collaboration have had to evolve. If cross-disciplinary learning has been difficult within TSBF, it has been even more so between TSBF and its partners, a fact which must be acknowledged before looking at the effectiveness of "participation" in the dealings of "researchers" with farmers.

This point needs to be based on what might be called "realistic expectations" of change. True collaboration must recognise (however reluctantly) that working with the human resources that are on hand within networks means starting from the perceptions and skills of those partners and moving at the best pace possible. It would have been easy to "cook" fancy results about participation if the social scientists had simply gone it alone. Working in partnership through AFNET, however, has forced TSBF to confront the realities of public funded research in Africa, the conservatism and logistical difficulties of which demand considerable patience. It is relatively easy for partners to influence each other's rhetoric, harder to alter each other's conceptualisations of problems, and harder still to make lasting changes in the way each carries out research tasks. "Participation" is not an approach whose benefits are learned or appreciated quickly and the socialisation of knowledge backwards and forwards between scientists and farmers depends fundamentally on the generation of experience.

The progress of AFNET towards "internalising" the rhetoric of farmer participatory research may seem glacially slow for being one of the more advanced scientific networks (cf. review of on-farm research in the EU-funded project, Carter *et al.*, 1998). As mentioned above, the scarcity of AFNET members trained in participatory methods able to act as "champions", and the lack of continuity in many institutions facing financial crisis, hinder the development of a more interdisciplinary research culture.

However, progress is being made in learning new attitudes and unlearning old ones. For example, the Zambian EU team decided to work on *fundikila* mound systems and to clear land on the research station to replicate the farmers' practices on-station, in full view of their peers. The Zimbabwean and Kenyan research teams have come to acknowledge the various micro-niches that farmers recognise and manage and have incorporated these into various research designs. Within the BMZ-funded project, increasingly sophisticated understanding of wealth and gender differences as they relate to soil fertility management have been incorporated into the project design. Finally, previously distinct elements of process and on-farm research have been combined in activities where complex soil-crop scenario modelling has been fed back into negotiation or decision support work conducted with farmers.

3.3. The politics of community-based research

It is, of course, never easy to surrender control of research agendas, even where the research is ostensibly for the benefit of the rural poor (i.e.: TSBF's Theme 1 is "Empowerment of Farmers" with new technologies). If TSBF has seemingly embraced what Ashby (1992) calls the "devolution to farmers [or other stakeholders] the major responsibility for adaptive testing and sharing of accountability for quality control over research", what have the political implications of this move been? Examples relating to defining innovation, the use of local youth as enumerators, and the micro-political dynamics of groups demonstrate.

3.3.1. Defining "innovation"

Farmer participatory research activities at TSBF began in community settings where portions of land were already being hired for research-designed activities, including both "pure" experimental treatments and "demonstration" plots to showcase the presence of nutrient deficiencies or the efficacy of various technologies. These activities tend to cloud the local understanding of what "research" actually is or can be, creating a sense that research generates information that "important" (the payments for land are known locally) but which comes in forms not readily accessible or understandable to "ordinary people". Even when experimentation has been ostensibly "turned over" to farmers, it is common to hear the new technologies being referred to as "belonging to the researchers".

Beyond a basic unfamiliarity with the intentions and operationalisation of collaborative research with scientists, there is the problem that many of the "experimentation" activities undertaken do not provide ideal venues for farmers to innovate in ways familiar to them. TSBF has a goal of providing farmers with a "basket of options" for ISFM (Swift *et al.*, 1994), including legume cover crops, improved fallows, biomass transfer (cut-and-carry) systems, improved compost manure, and various combinations of organic and inorganic fertilisers. In the EU and BMZ-funded projects, after initial PRA's in the communities, farmers were given the chance to select technologies from this "basket" to try on their own land. Selection of otherwise completed technologies, however, is not the same as participating in the technology design process.

The "over-designing" of technologies before involving farmers in their development is a natural consequence of scientists failing to a) trust in the innovative capacity of farmers or b) know how to apply farmers' knowledge and innovation as contributions to "formal" scientific activity. It limits farmers' role to relatively passive activities, such as selecting niches or adapting application rates to local circumstances, which ultimately discourages any sense of ownership of the technology development process. However, to recognise certain behaviour as an "innovation" requires channels of communication and trust to exist between farmer and scientist, and a willingness to see all modifications of practice (including abandonment and complete reversals) as potentially useful.

Observations of innovative farmer practice can feed into researchable topics, such as the use of Tithonia as a nutrient-rich mulch (now a staple "technology" promoted by TSBF and others in East and Southern Africa). When translating the Tithonia biomass transfer technology to other farms, a commonly heard comment is that the cut-and-carry system is "labour intensive". Harvesting biomass from hedgerows all at once before planting one's crops is indeed a large, and previously non-existent task, even if pruning hedgerows or applying plant material on cropland are familiar activities already in the household calendar. As a result, many farmers have begun harvesting their Tithonia sporadically (as part of normal hedge maintenance) and transferring it to their compost pile (another familiar task). Clearly the decision not to continue with the cut-and-carry operation and instead supplement the compost pile with Tithonia should be seen as an "innovation" or indeed as a logical supplementation of existing practices. However, while Tithonia had been identified as a "best bet" for direct application to fields since it decomposes so rapidly, it may not be the "best" option for materials to be added to compost piles that sit for a time before application. A natural entry point for truly interdisciplinary research is experimentation based on farmers' own practices (many report that Tithonia speeds the "cooking" of compost piles making it ready for use sooner) to validate the use of Tithonia or alternative materials as part of the composting process.

3.3.2. Local youths as enumerators

Among the many tools and approaches used for conducting its social fieldwork in Western Kenya in the early 1990s, TSBF relied on young and literate people, recruited from the local communities as enumerators. They were typically given basic training that would allow them to support "community-level" research activities such as questionnaire administration and the setting up of trial plots. Over time, they began to take on more responsibilities, received further training, and by 1997 were facilitating farmer-led experimentation. However, personnel changes at TSBF, and attitudinal differences between TSBF on the one hand, and the local partner KARI (Kenya Agricultural Research Institute) on the other, had important implications for the role of these enumerators and the work they carried out.

TSBF staff had viewed the capacity development of these youth as part of a community-based learning strategy to build rapport with other farmers. Indeed, the local communities were openly sympathetic to this approach, since it provided immediately tangible benefits to locals employed as enumerators, and also ensured that research was carried out by people who would be familiar to community-members and at home with the local cultural norms and vernacular. However, what was perhaps never explicit was how (if at all) the inclusion of these enumerators in project activities differed from the way that other local people were trained to work on experimental plots as paid labourers.

During the interval between Carter's departure and Sikana's arrival, the enumerators carried on their work, with backstopping where possible from KARI. However, without strong advocacy for participatory methods rather than more top down approaches, KARI staff tended to view the enumerators who were already "part of the community" as a useful channel for "passing useful scientific skills and knowledge *into* the local community". At the same time, because of their training, regular association with TSBF staff, and the perceived status benefits accruing from their employment, many of the enumerators tended to count themselves more as part of *TSBF* than as part of the "*community"*. In the end, this distancing between enumerator and community (enhanced by youth and the fact that many of the enumerators did not themselves farm) undermined their ability to link farmers and researchers effectively.

Since then, an effort has been made to build individual capacity within KARI and the national extension service for participatory research. Currently, an agricultural extension agent who speaks the local dialects has been hired for facilitating community-based input. This expert works with community groups, farmer field schools (FFS), individual farmers and other local stakeholders. However, as with the enumerators, these activities have demanded considerable backstopping by the Social Science Officer and other disciplines within TSBF.

3.3.3. The micro-politics of groups

As TSBF placed more attention on building capacity in its partners for farmer participatory research, it also shifted to working with local farmers as groups and individuals. In the earlier 1990s, on-farm trials were based on individual's farms. In such arrangements, host farmers were expected to define and explain experiments to other local and visiting farmers. While we do not know the exact accomplishment through this arrangement, there are indications in Kabras and Vihiga that selecting "model" farmers to work with disaffects them from many other farmers.

Down the road, focus shifted to the group approach. Initially, it seemed obvious that involving many farmers would have a multiplier effect. However, it soon became apparent that the *manner* in which TSBF talks to *whom* is more important than mere numbers. Groups are on frequently unstable and many are not especially open to new membership. When researchers request farmers to work with them collectively, "new" groups emerge. But these "new" groups usually comprise members of a previous, defunct group. This means that one has to *deliberately* seek the inclusion of all types of farmers (within and outside groups) in research and dissemination. This role of a local unifier is tricky and can even appear comical before local farmers.

Intervening research on the nature of social capital and the role of local groups and networks in passing agricultural information (Misiko, 2001) has shown that there is still a tendency for some groups or individuals to view their participation in TSBF as "secret knowledge" that is not to be shared with others. Likewise, non-participants are often wary of inquiring about project activities, assuming that they are not welcome or need to be invited by some patron. This attitude has persisted for multiple reasons, and in spite of the considerable efforts of TSBF and other research bodies to present their work as "open to all" by actively seeking to include marginalized groups. Because local politics takes precedence even over the "good intentions" of outsiders, the vast exposure that many farmers have had to project work in Western Kenya does not, therefore, translate into widespread use or understanding of ISFM.

The initial willingness of TSBF to accept "groups" as representatives of community interests has led to numerous problems. After all, groups exist and persist when they have strong roles and identities, histories of their own which often only become known with time. For example, the most vocal members of groups have frequently been people who are either not well respected by others locally, or possessed of agendas that run far beyond ISFM. This later group tends to see the research project as a vehicle for access to new resources and political leverage than as an opportunity for new learning (Sikana, 1995), although it may take project staff a long time to appreciate this reality. Since much of TSBF's on-farm work has been initiated in the context of structural adjustment programmes and the cessation of donor funding for major local development projects, it is natural that farmer concerns about water, health, poor infrastructure, or education would be mapped onto the "research" activities if TSBF was the only "development" agency working in their area. Beyond such explicit "hijacking" of groups, there are frequently tensions between participants over the definitions of goals, membership, and indeed the "success" of the group's activities.

Nevertheless, working through groups provides an opportunity to diffuse risk and broaden responsibility and ownership of activities. Groups should be seen neither as a panacea for community-based management's difficulties, nor as a replacement for effective dissemination strategies. When setting up experiments or demonstrations at the local level, having wider input about where in the landscape, whose land, or which soils are suited to which types of research activity has proven invaluable. With our broadened knowledge of the diversity of local soil types, requests by farmers to have activities replicated on different soils become logical and understandable, when previously they might have been dismissed as unjustified demands for a share of a perceived research "pie". In the end, such replication turns out to be both good science and good politics.

4. Strategic lessons: finding common ground

4.1. Building on the easiest topics

The challenges that TSBF has tried to address are highly complex in both biophysical and social terms. As such, interdisciplinary collaboration depends on developing a better understanding of what changes are taking place, and of developing a modus operandi that can generate useful knowledge as part of an on-going dialogue between scientists and farmers.

The parallel dialogue that must take place, between social and natural scientists, has been easiest around themes that integrate themselves readily into natural science work, including spatial variability, wealth ranking and ISFM practice, and the importance of understanding the strengths and weaknesses of existing local knowledge. It has been considerably harder to incorporate elements that relate to the political nature of "research", such as using livelihoods analysis or feminist political ecology to find the place of ISFM and research interventions within local practice.

4.2. Championing workable models

If AFNET collaborators have been slow to adopt interdisciplinary and participatory approaches, it is due in part to the relative lack of successful, convincing models of how such approaches pay short or long-term benefits to NRM research. Further constraints have been staff turnover (which leads to fragmented agendas and loss of institutional memory), scarcity of time and resources, and a shortage of generalists or social scientists within partner organisations. The rhetoric of interdisciplinarity and participation have rapidly infiltrated research bodies because they are relatively cost free and often there is the perception that donor funding is linked to such language. Simplified versions of interdisciplinary activities, linking ISFM with participatory wealth ranking, or moving from local soil taxonomies to broader understanding of how soil fertility is managed locally, have also begun to take hold within local practice. While some natural scientists are "afraid of having to become social scientists", there is a slowly growing constituency within AFNET that sees advantages for interdisciplinary collaboration. Nevertheless, without relatively senior "champions" for interdisciplinary or socially oriented approaches within TSBF, new methods and approaches are at a disadvantage compared with the more familiar status quo.

4.3. Negotiating the role and nature of "research"

Given the variables of donor climate, institutional and personnel changes, and socio-political change on the ground, truly interdisciplinary INRM research will need to develop a common language and common priorities that can form a core identity in dealing with outside forces. This requires an iterative process of negotiating the role of "research" in the development of local communities. If donors, researchers, and extensionists feel the need to "scale up" local successes and achievements to *broader* communities, it must be reconciled with the desires of the initial community members for taking research accomplishments to greater *depth*. If moving towards group-based research methods means shifting the burden of implementation to national partners, a common path for "participation" will need to be negotiated. In particular, the skills and attitudes necessary to support more decentralised forms of research need to be cultivated by the scientists, agents, and farmers involved.

Despite the rhetoric of interdisciplinary collaboration, cross-disciplinary learning and communication remain complicated by the divergent ideas of what role "research" can and should play in bringing about change in rural communities. Resolving these divergences often falls to social scientists, since their disciplinary orientation predisposes them to thinking about such issues and their colleagues are more likely to see these issues as somehow separate from their daily activities of research. However, building common bodies of knowledge and practice can only happen with the full participation of all disciplines involved in INRM. If we look at how far an organisation like TSBF has come in ten years, from research foci that concentrated on the integration of biological processes to ones which now embrace the livelihoods and knowledge of the farmers who practice integrated soil fertility management, there is room for hope.

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Modelling nitrogen mineralization from organic sources: representing quality aspects by varying C:N ratios of sub-pools

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Abstract

The mineralization/immobilization of nitrogen when organic sources are added to soil is represented in many simulation models as the outcome of decomposition of the added material and synthesis of soil organic matter. These models are able to capture the pattern of N release that is attributable to the N concentration of plant materials, or more generally the C:N ratio of the organic input. However the models are unable to simulate the more complex pattern of N release that has been reported for some animal manures, notably materials that exhibit initial immobilization of N even when the C:N of the material suggests it should mineralise N. The APSIM SoilN module was modified so that the three pools that constitute added organic matter could be specified in terms of both the fraction of carbon in each pool and also their C:N ratios (previously it has been assumed that all pools have the same C:N ratio). It is shown that the revised model is better able to simulate the general patterns on N mineralised that has been reported for various organic sources. By associating the model parameters with measured properties (the pool that decomposes most rapidly equates with water-soluble C and N; the pool that decomposes slowest equates with lignin-C) the model performed better than the unmodified model in simulating the N mineralization from a range of feeds and faecal materials measured in an incubation experiment.

Keywords: decomposition, mineralization, quality factors, simulation, modelling

1. Introduction

The cycling of nutrients through the decomposition of plant residues is important in all ecosystems. However in the soil fertility management of many tropical farming systems, organic sources play a dominant role because of their short-term effects on nutrient supply to crops (Palm et al., 2001). There is now a considerable literature reporting decomposition and nutrient release patterns for a variety of organic materials from tropical agro-ecosystems. This information has been drawn together so that it can be used for improvement of soil fertility through better management of organic inputs (e.g. Giller and Cadisch, 1997; Palm et al., 2001), and understanding has emerged of how resource quality factors influence the release patterns.

In nutrient and capital poor tropical farming systems, effective use of whatever nutrient sources are available will be required to raise and maintain productivity (Giller et al., 1997). If models are to be useful in helping to design farming systems that use various nutrient sources more effectively, it is a first requirement that the models must be able to reliably describe the release of nutrients from the different organic sources. Palm et al. (1997) pointed out that there is little predictive ability for making recommendations on combined use of organic and inorganic nutrient sources. One reason for this is the inability of models to adequately capture the short-term dynamics of the release of nutrients from organic materials.

In this paper we report on how one particular model, APSIM (Agricultural Production Systems Simulation Model, McCown et al., 1996; Keating et al., 2002), represents the decomposition of organic inputs, and how the quality of the inputs influences nitrogen release. The manner in which the dynamics of soil carbon and nitrogen are modelled in APSIM's SoilN module (Probert et al., 1998) is similar to what is found in many other models - see reviews by Ma and Shaffer (2001) and McGechen and Wu

(2001). Models do differ in the pool structure used to describe the decomposition of organic inputs, with the pools differing in their rates of decomposition. However, we are unaware of any model where the pools differ in chemical composition, with the effect that inputs decompose with non-varying composition. We show that the assumption that all pools have the same C:N ratio fails to adequately represent the observed behaviour for release of N from some organic inputs. We present a modification of APSIM SoilN which allows for different C:N ratios in each pool. The modified model was able to better match the mineralization/immobilization of N observed in laboratory incubation studies.

2. Modelling the decomposition of organic sources

The development of the APSIM SoilN module (Probert et al., 1998) can be traced back via CERES models (e.g. Jones and Kiniry, 1986; Godwin and Jones, 1991) to PAPRAN (Seligman and van Keulen, 1981). Briefly, crop residues and roots added to the soil, are designated fresh organic matter (FOM) and are considered to comprise three pools (FPOOLs), sometimes referred to as the carbohydrate-like, cellulose-like and lignin-like fractions of the residue. Each FPOOL has its own rate of decomposition, which is modified by factors to allow for effects of soil temperature and soil moisture. For inputs of crop residues/roots it has usually been assumed that the added C in the three FPOOLs is always in the proportions 0.2:0.7:0.1. In this manner the decomposition of added residues ceases to be a simple exponential decay process as would arise if all residues were considered to comprise a single pool.

Although the three fractions have different rates of decomposition, they do not have different compositions in terms of C and N content. Thus whilst an input might be specified in terms of the proportion in each of the FPOOLs, thereby affecting its rate of decomposition, the whole of the input will decompose without change to its C:N ratio. If the analogy can be made with the dissolution of a substance, we might say that the whole of the residues decompose congruently. Alternatively the system can be described as having three soil organic C pools but only one soil organic N pool (Gijsman et al., 2002).

The release of N from the decomposing residue is determined by the mineralization and immobilization processes that are occurring. The C that is decomposed from the residue is either evolved as CO_2 or is synthesized into soil organic matter. APSIM SoilN assumes that the pathway for synthesis of stable soil organic matter is predominantly through initial formation of soil microbial biomass (BIOM), though some C is transferred directly to the more stable pool (HUM). The model further assumes that the soil organic matter pools (BIOM and HUM) have C:N ratios that are unchanging through time. The formation of BIOM and HUM thus creates an immobilization demand that has to be met from the N released from the decomposition of the residue and/or by drawing on the mineral N (ammonium- and nitrate-N) in the system. Any release of N during the decomposition process in excess of the immobilization demand results in an increase in the ammonium-N. The model operates on a daily time step, so that decomposition of the residue fractions is happening simultaneously with decomposition of the soil organic matter pools.

If we ignore the dynamic nature of the system, the N mineralization from a substrate can be expressed succinctly as (Whitmore and Handayanto, 1997):

$$N_{mineralized} = C_{decomposed} \{1/Z - E/Y\} \quad \ldots\ldots \text{ equation (1)}$$

where Z is the C:N ratio of the decomposing substrate, E is a microbiological efficiency factor which can be taken to be 0.4 (the value in APSIM SoilN for the fraction of the decomposing carbon that is transformed into soil organic matter), and Y is the C:N ratio of the soil organic matter being formed. Equation (1) implies that there is a C:N ratio of substrate that determines whether decomposition results in net N mineralization or immobilization. Assuming the initial product of decomposition is soil microbial biomass with Y = 8 (the value used in APSIM SoilN), the critical value can be calculated as 20. As shown by Whitmore and Handayanto (1997), this expression accounts for much of the variation found in the data that have examined N mineralized (or immobilized) in relation to the C:N ratio of the added organic matter.

The rate of net N mineralization is dependent on the rate of decomposition. Thus allowing the pool sizes of the three FPOOLs to be an input that characterizes the type of organic input will alter the rate of net N mineralization (as shown by Quemada and Cabrera, 1995; Quemada et al., 1997). However changing the pool sizes alone cannot alter whether a source exhibits initial net N mineralization or immobilization (since this is determined by the C:N ratio of the source).

In studies of the mineralization of N from various manures, Kimani et al. (2001) and Delve et al. (2001) encountered situations where there was an initial immobilization of N, despite the fact that the overall C:N ratio of the material was such that it would be expected to result in net mineralization. This behaviour can not be modelled without assuming that the three FPOOLs also differ in their C:N ratios.

2.1 Modifications to the model

Modifications were made to the APSIM SoilN module so that any input of organic material could be specified in terms of both its fractionation into the three FPOOLs, and the C:N ratios of each FPOOL. In the modified model, each FPOOL is assumed to decompose congruently. The rates of decomposition of the three FPOOLs were not changed from the released version of APSIM (0.2, 0.05 and 0.0095 day^{-1} respectively under non-limiting temperature and moisture conditions).

Using this enhanced version of the model, we have explored the effects on simulated N mineralization from hypothetical sources that differ in respect of firstly, their fractional composition (the proportion of C in the 3 FPOOLs), and secondly, the C:N ratios of the FPOOLs.

The effects are illustrated by contrasting four assumptions as to how an organic input decomposes:

1. using the released version of ASPIM SoilN (v 2.0)
2. changing the fractional composition of the FPOOLs but with the C:N ratio being the same in all pools
3. changing the FPOOLs to have different fractional compositions and different C:N ratios, in the first instance with FPOOL1 differing from a common value for FPOOLs 2 and 3
4. with the fractional composition and C:N ratios differing between all 3 FPOOLs.

2.2 Specification of model inputs

The enhancements made to the model result in extra information being needed to specify the inputs. Ideally it should be possible to derive the necessary information from known (measured) properties of the organic sources.

The experimental data reported by Delve et al. (2001) have been used to investigate whether the analytical data for a range of feeds and faecal samples can be used to specify the model to simulate the N mineralization measured in a laboratory incubation experiment.

3. Materials and Methods

3.1 Simulation of mineralization from hypothetical sources

The model was configured to simulate a simple incubation study, involving a single layer of soil under conditions of constant temperature (25^{o}C) and at a soil water content that ensured there was no moisture restriction on decomposition. Initial nitrate-N concentration in the soil was 20 mg N kg^{-1}. The effect of different organic inputs was investigated by incorporating materials that contained a constant amount of N (100 mg N kg^{-1} soil) but with varying C:N ratio. A control system was also simulated without any added organic input.

The output from the simulations are presented as net mineralization/immobilization expressed as a percentage of the N added:

$$\text{N mineralization (\%)} = 100 \times (\text{Mineral-N}_{\text{input}} - \text{Mineral-N}_{\text{control}})/\text{N added}$$

where Mineral-N_{input} is the simulated ammonium- + nitrate-N in systems with the added source, and Mineral-$N_{control}$ in the absence of any input.

3.2 Simulating a laboratory incubation study

The model was specified to simulate the incubation study of Delve et al. (2001). Using a leaching tube incubation procedure (Stanford and Smith, 1972), they measured net N mineralization for feeds and faecal samples resulting from cattle fed a basal diet of barley straw alone, or supplemented with 15 or 30% of the dry matter as *Calliandra calothyrsus*, *Macrotyloma axillare* or poultry manure. The soil used was a humic nitisol with organic C content of 31 g kg^{-1}, C:N ratio of 10 and pH (in water) of 5.9. The incubations were conducted at 27^{o}C.

Data were reported on the chemical composition of the feeds and faecal samples including: total C and N; water soluble C and N; acid detergent fibre (ADF), neutral detergent fibre (NDF) and acid detergent lignin (ADL) (van Soest et al., 1987).

4. Results

Experimental data (Kimani et al., 2001), that indicated the need to reconsider how N mineralization from organic inputs is modelled, are illustrated in Figure 1. For a wide range of manures, their results consistently show an initial immobilization or delay in mineralization lasting several weeks, even for materials that have overall C:N ratios of less than 20. This pattern of response is noticeably different to studies of N mineralization from plant materials (e.g. Constantinides and Fownes, 1994); plant materials with low C:N typically exhibit positive net mineralization from the commencement of the incubation period.

Other authors also report initial N immobilization followed by net mineralization in experiments with animal manures having low C:N ratios (Trehan and Wild, 1993; Olesen et al., 1997). The faecal samples studied by Delve et al. (2001), with C:N ratios in the range 20-27, had even more complex patterns of mineralization; some materials showed initial net mineralization before an extended period of immobilization lasting for at least 16 weeks of incubation (see below).

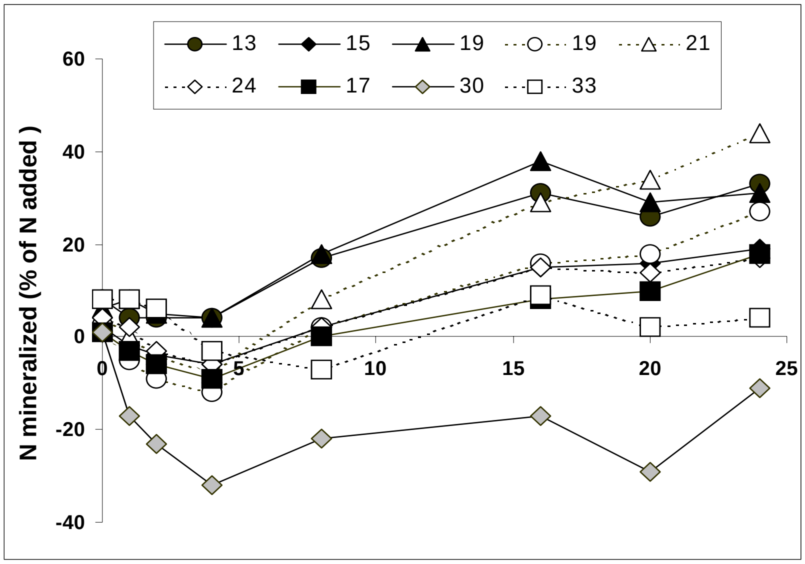


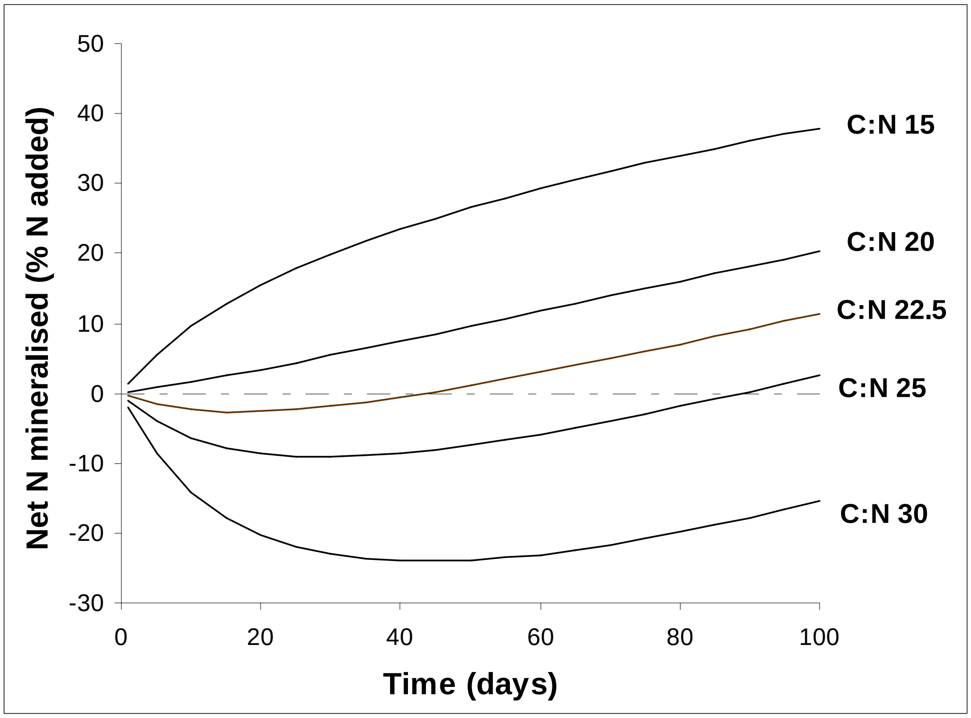
Figure 1. Net nitrogen mineralised from different manures in an incubation study lasting 24 weeks. C:N ratios of the manures are shown in the legend. Data of Kimani et al. (2001)

4.1 Modelling N mineralization from hypothetical sources

Simulation of mineralization for sources with different C:N ratios using the released version of APSIM SoilN is shown in Figure 2. The results are in general agreement with experimental studies for plant materials where net N mineralization is closely related to the N content and hence C:N ratio (e.g. Constantinides and Fownes, 1994; Tian et al., 1992). For sources with C:N < 20, net mineralization occurs from the outset (as predicted by equation 1). However with C:N > 20, there is initially immobilization of mineral-N and it is only as newly formed soil organic matter is re-mineralized that mineral-N in the system begins to increase.

The lower pane of Figure 2 shows the same data plotted against the C:N ratio for different periods of incubation. Again the pattern of response is familiar from experimental data that have been used to infer the C:N ratio of a substrate, around 20-25, that determines whether net mineralization or immobilization occurs. The simulation results show that the C:N ratio of the substrate that results in zero net mineralization changes with the period of incubation, increasing from approximately 21 at day 10 to 26 at day 100. Such an effect has not generally been recognized when discussing critical C:N ratios with respect to mineralization/immobilization, though its importance was recognized by De Neve and Hofman (1996). Thus incubation period is a factor that will complicate efforts to compare results from different incubation studies. Furthermore other aspects of the incubation conditions can also be expected to have similar effects as the incubation period; in particular higher incubation temperature is likely to have much the same effect as increasing the incubation period.

The effect of changing the pool structure of the input by modifying the fractions in each of the FPOOLs is illustrated in Figure 3. For inputs with low C:N (<20), a greater proportion of material in the FPOOLs with lower rates of decomposition simply slows the release of mineral-N. Where C:N is >20 so that net immobilization occurs, inputs with a greater proportion of material with lower rates of decomposition result in less immobilization during the early stages of decomposition, but it also takes longer before the system exhibits positive net mineralization. It is to be noted that simply changing the proportions of the input between the three pools with unaltered C:N ratio can not cause a switch from causing net mineralization to immobilization, or vice versa.



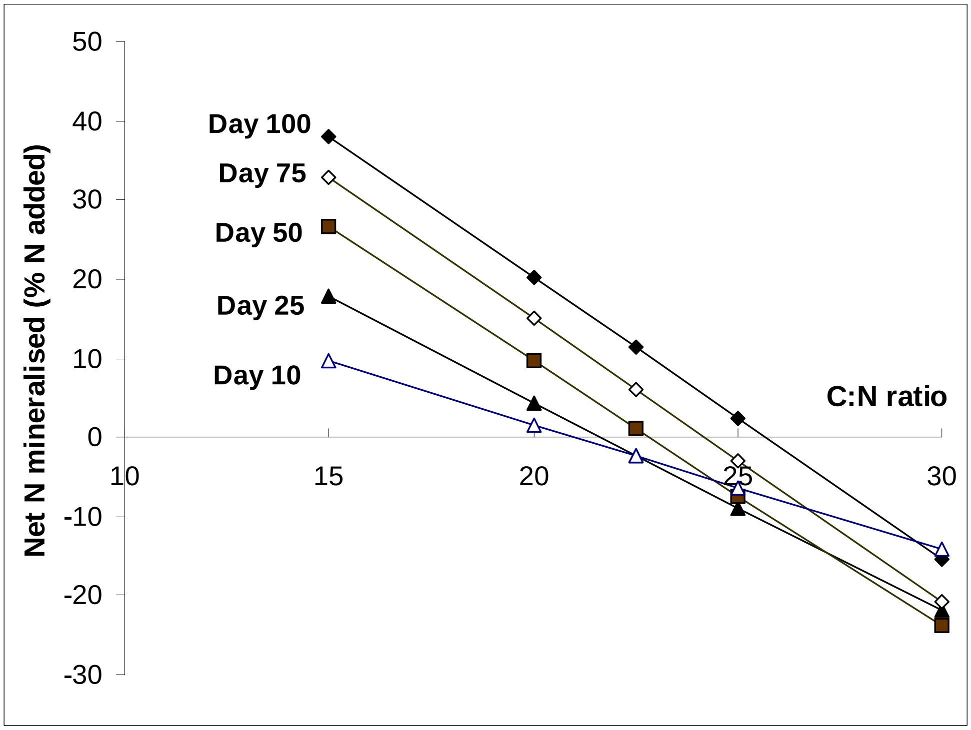


Figure 2. Simulation of nitrogen mineralization from organic inputs with different C:N ratios using the released version of APSIM SoilN. The model assumes that all inputs have the same fractional composition in terms of the three FPOOLs (0.2:0.7:0.1), and that, for a given source, all FPOOLs have the same C:N ratio.

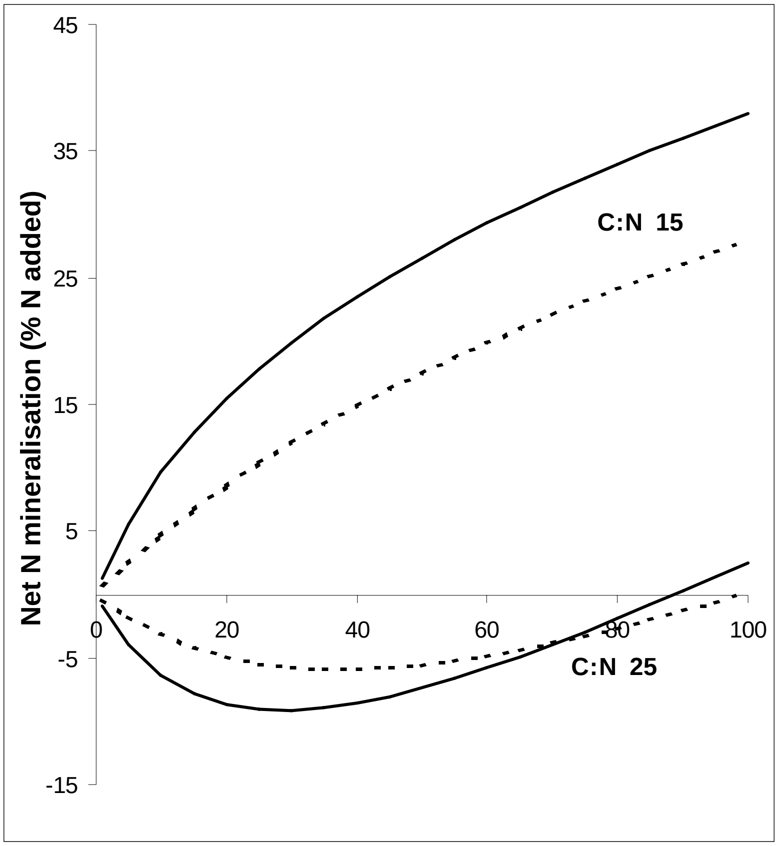


Figure 3. Effect of changing the composition of organic inputs by varying the proportions in the three FPOOLs. The continuous lines refer to substrates where FPOOLs comprise 0.2:0.7:0.1 of the total carbon; the dashed lines 0.01:0.49:0.5. The C:N ratios of all FPOOLs (for a given source) are the same.

Effects of changing the composition of the input by modifying the C:N ratios of the different FPOOLs are shown in Figures 4 and 5. In Figure 4, all materials have the same overall C:N ratio, but the C:N ratio of FPOOL1 is now greater than for the material in pools 2 and 3. The result is that the material in FPOOL1 which decomposes most rapidly creates an immobilization demand, and the higher the C:N ratio the greater the initial immobilization. However if C:N of FPOOL1 is higher, there must be compensating decreases in the C:N ratios of the other pools. As incubation time increases, the differences between different materials decrease so that there is little longer-term effect of the C:N ratios of the FPOOLs on net mineralization which is determined largely by the overall C:N ratio.

Figure 5 illustrates variation in the C:N ratio between FPOOLs 2 and 3. Again all materials have the same overall C:N ratio and here the C:N of FPOOL1 is also fixed at 10. With the low C:N in the rapidly decomposing pool, there can be an initial net mineralization, especially when the C:N of FPOOL2 is also relatively low. However, as FPOOL1 is depleted, there can be a switch from net mineralization to net immobilization. Increasing the C:N of FPOOL2 results in increasing immobilization and the immobilization persists to longer times.

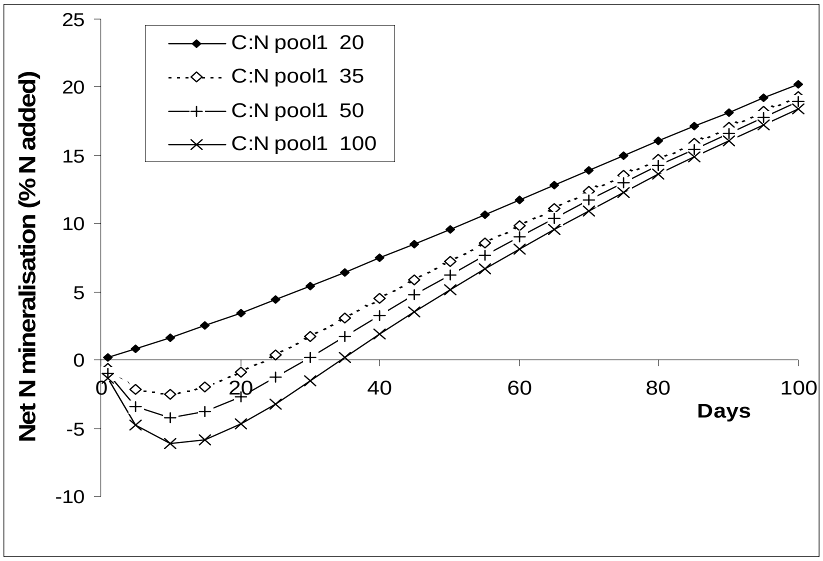


Figure 4. Effect of changing the composition of organic inputs by modifying the C:N ratios of the FPOOLs. In this example, the input has fractional composition 0.2:0.7:0.1 and overall C:N ratio of 20, with the C:N ratio of FPOOL1 as shown in the legend (C:N ratios of FPOOLs 2 and 3 are equal)

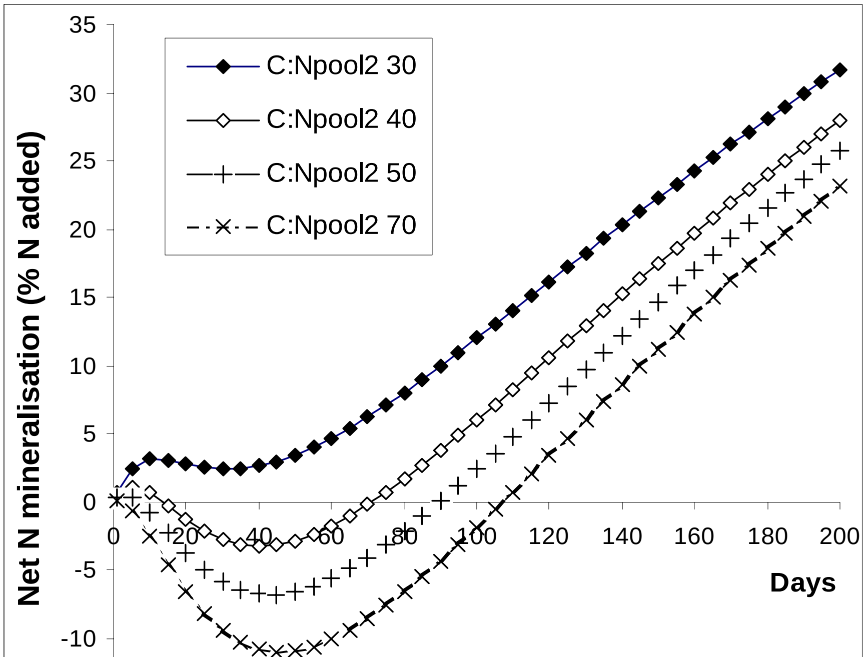


Figure 5. Effect of changing the quality of organic inputs by varying the C:N ratios of the FPOOLs. In this example, the input has fractional composition 0.1:0.7:0.2, overall C:N ratio of 20 and C:N ratio of FPOOL1 of 10, with C:N of FPOOL2 as shown in the legend.

4.2 Modelling the mineralization study of Delve et al. (2001)

The modelled net mineralization from hypothetical sources display patterns of N release that are similar to published experimental data. Notably the several weeks delay before mineralization became positive, as exhibited by several of the manures studied by Kimani et al. (2001), is consistent with variation in the C:N ratio of FPOOL1 (Figure 4). On the other hand, the longer delay reported by Delve et al. (2001) is more like the pattern shown in Figure 5 associated with variation in FPOOL2 and 3.

We have attempted to use the analytical data reported by Delve et al. (2001) to specify the "quality" aspects of organic inputs represented in the model. We assume the soluble components of C and N equate to FPOOL1; thus the analytical results are sufficient information to determine the proportion of total C in this pool and its C:N ratio. Also we assume that ADL, which measures lignin, equates to FPOOL3 permitting the fraction of C in this pool to be estimated; the fraction of C in FPOOL2 is found by difference. Since the overall C:N ratio (on a total dry matter basis) is also known, the only missing information is the distribution of non-water soluble N between pools 2 and 3. A series of simulations were carried out for each source with the different combinations on C:N in the two pools (constrained by the C:N of the total DM).

Figure 6 shows the simulation of N mineralization for the control treatment. Although there is a slight under-prediction, the general pattern agrees well with the measured data. It is to be noted that in the model the net N mineralization from an organic source is only influenced by the control treatment when there is inadequate mineral N in the system to meet an immobilization demand.

The net N mineralization for the feeds and a selection of the faecal samples studied by Delve et al. (2001) is shown in Figure 7. The outputs from two simulations are compared, these being the outputs from the modified and unmodified versions of the model. The input data used for the modified model are set out in Table 1.

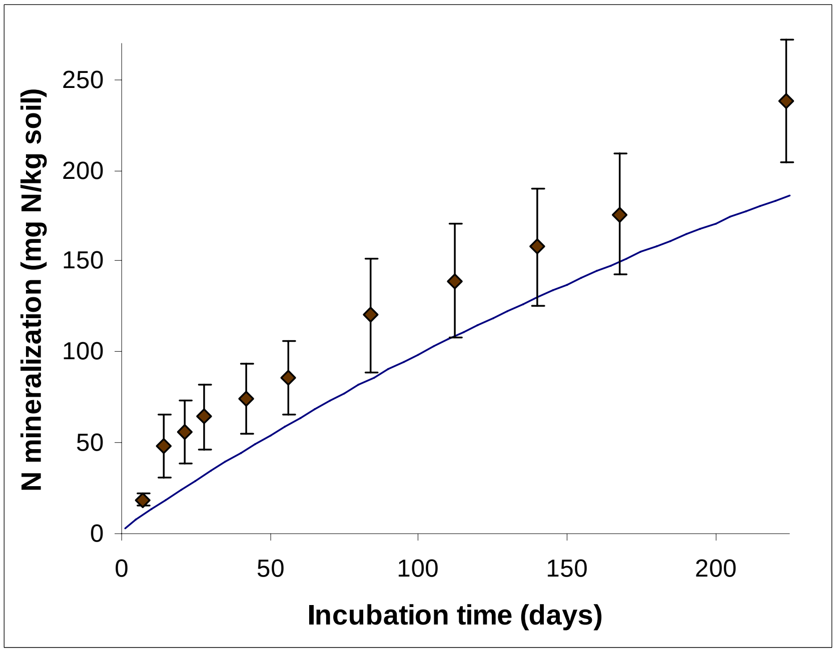


Figure 6. Simulation of the control treatment of Delve et al. (2001). The symbols denote measured data with error bars representing □standard error of the mean of 3 replicates. The continuous line is the output from the model. Overall C:N ratio was measured; FPOOL1 based on measured C and N as water soluble components; proportion of C in FPOOL3 based on measured ADL. C:N of FPOOL2 and 3 selected, subject to constraint that must be consistent with overall C:N, to give reasonable fit between simulated N mineralization and measured data.

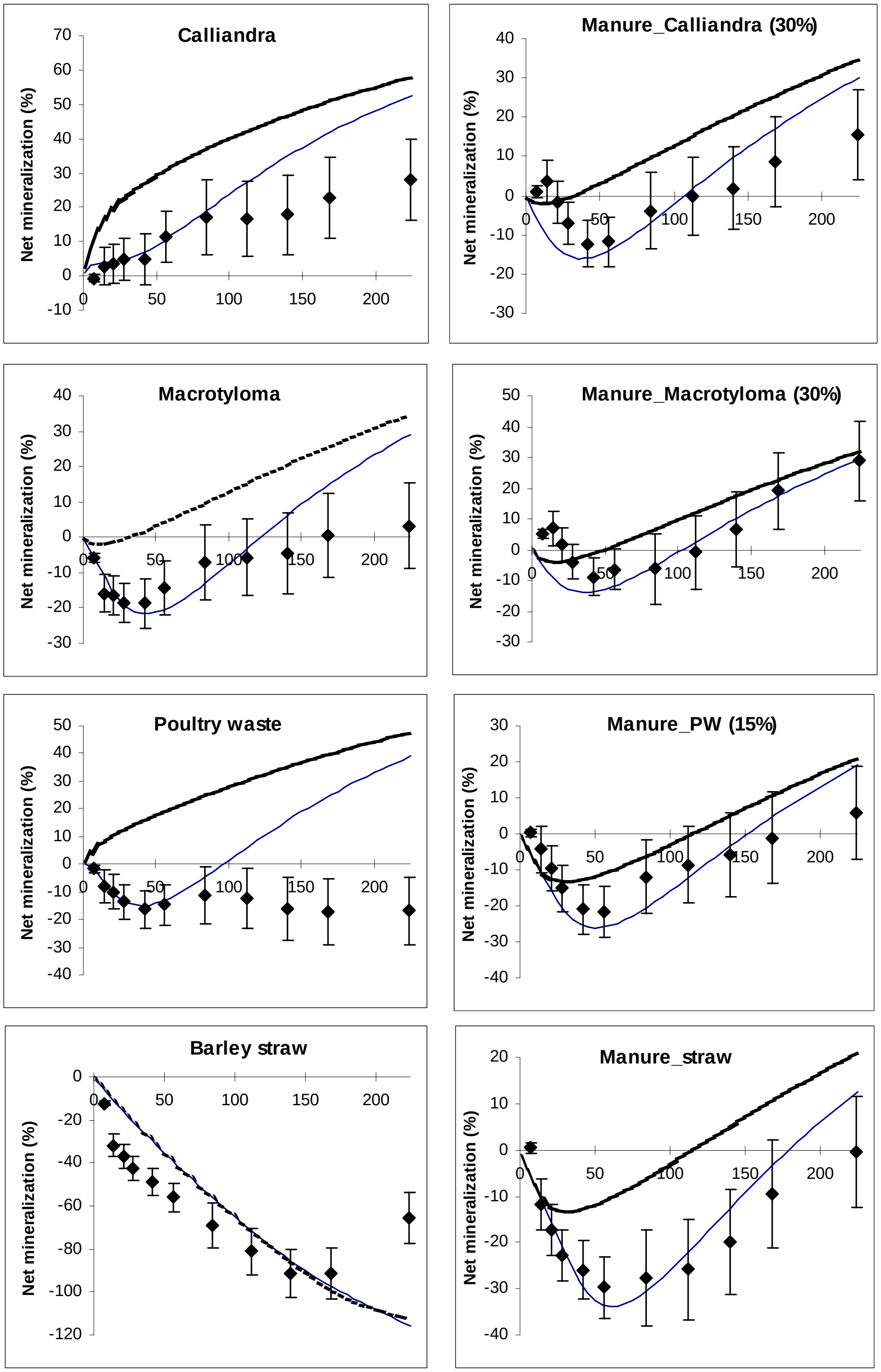


Figure 7. Net nitrogen mineralization from feeds and faecal materials (data of Delve et al., 2001). Experimental data shown as symbols with bars representing □ standard errors. The heavy broken line is for the model where all organic material is assumed to decompose with the same C:N ratio; the continuous line is for the model with different C:N ratio in each FPOOL. Parameters used to specify the different sources (proportion of C and C:N in the three FPOOLs) are set out in Table 1.

Table 1. Composition of organic materials (feeds and faecal samples) used for simulating the mineralization study of Delve et al. (2001).

Sample	**Overall C:N**	**Proportion of carbon in FPOOLs (%)**			**C:N of FPOOLs**		
		Pool 1	**Pool 2**	**Pool 3**	**Pool 1**	**Pool 2**	**Pool 3**
Calliandra	13	12	74	14	9	44	3
Macrotyloma	22	16	74	10	17	67	4
Poultry waste	17	5	88.5	6.5	4.5	202	1.5
Barley straw[1]	86	6	84.5	9.5	24	103	103
Calliandra_Manure (30%)[2]	22	4	74	22	16	40	9
Macrotyloma_Manure (30%)	23	5.5	73.5	21	14	36	11
Poultry waste_Manure (15%)	27	4.5	82	13.5	12	41	10
Barley straw_Manure	27	9	71.5	19.5	20	66	9

[1] simulated N mineralization was not sensitive to partitioning of N between pools 2 and 3

[2] value in parentheses denotes proportion of supplement in diet

For most of the materials the goodness of fit is substantially better for the modified than for the unmodified model. Using the analytical data to specify the fraction of C in each of the FPOOLs and the C:N ratio of FPOOL1, it was possible to choose values for the C:N ratios of FPOOL2 and FPOOL3 to obtain satisfactory fits with the measured data.

In general the fit is better for the faecal samples than for the feeds, with the poorest fit for the poultry waste. The pattern of net mineralization measured for the poultry waste, which had an overall C:N ratio of 17, is different from the other materials in that the change from immobilization to mineralization that occurred after 50 days was not maintained, and further net immobilization occurred later in the incubation. The simulation for the barley straw (C:N 86) predicts that immobilization continues for at least 200 days. Because all mineral N is immobilized in this treatment, the simulated immobilization is determined by the rate of mineralization of the control treatment and is not sensitive to how N is partitioned between FPOOLs 2 and 3. The under-prediction of N mineralization in the control treatment (Fig. 6) is the cause of the under-prediction of net immobilization by the barley straw.

5. Discussion

The essence of equation (1) is built into many dynamic simulation models that describe the decomposition of organic residues and the associated mineralization of N. Such models are capable of capturing the gross effect of C:N ratio (as illustrated in Fig. 2) on mineralization/ immobilization from plant residues. However they are not able to represent the more complex pattern of mineralization/immobilization that has been reported from laboratory incubation studies of N release from manures with low C:N (e.g. Fig. 1). To capture this pattern of N release it is necessary to conceptualize the organic input as comprising discrete fractions that differ not only in their rates of decomposition but also in their chemical (i.e. C and N) composition.

The observed behaviour suggests that the fraction of the substrate that decomposes fastest has a higher C:N ratio than the bulk of the material. If the portion that decomposes fastest can be equated to the water-soluble fraction, this is consistent with the analytical data of Kimani et al. (2001) (Table 2). Their data show that the soluble component, which amounted to some 12% of the total carbon, had a much higher C:N ratio than the materials as a whole.

Table 2. Carbon and C:N ratio in manures and their water soluble fraction. Data are means, with standard deviation in parentheses, across 45 diverse manure samples. Data of Kimani et al. (2001)

	% C	C:N ratio
Total	32 (7.0)	21 (5)
Soluble fraction[1]	3.8 (1.9)	68 (60)

[1] soluble C expressed on total DM basis (i.e. average of 12% of total C was measured in the soluble fraction)

In contrast, the mineralization data of Delve et al. (2001) (Fig. 7) and chemical composition of their materials (Table 1) indicate that the measured water-soluble component had a smaller C:N than the bulk materials. To simulate the observed mineralization data it was necessary to assume that the materials had higher C:N in FPOOL2 than in FPOOL3.

To some extent, this difference between in the C:N of the water-soluble components in the two studies can be explained by the nature of the manures. Those in the study of Delve et al. (2001) were fresh faecal material, whereas the manures studied by Kimani et al. (2001) had been collected from farm situations where they would have been exposed to varying degrees of weathering what would have been expected to remove some water-soluble components. However if this is the explanation, we are unable to satisfactorily account for why the analytical data of Kimani et al. (2001) should still indicate considerable amounts of water-soluble C, nor why there should have been preferential loss of N relative to C resulting in increased C:N for the water-soluble components.

By simulation of hypothetical materials, we have shown that the model can be parameterised to simulate the general pattern of N mineralization that is observed for various organic sources. Nonetheless, it remains a challenge to know how appropriate parameters should be selected for a given source and/or how to derive the parameter values from other information that may be available as analytical data for supposed "quality factors". Here we have used data for C and N in the water-soluble components to specify FPOOL1, and the measured ADL to specify the C in FPOOL3. To obtain the goodness of fit shown in Fig. 7 for the manures required C:N in FPOOL2 in the range 36-66, with corresponding C:N in FPOOL3 of 9-10 (Table 1). Attempts to estimate the C:N of FPOOL2 from measured data for N associated with ADF and NDF (Delve et al., 2001) produced values that were considerably higher (range 63-174 for the manure samples) with the corresponding values for pool 3 becoming very narrow (<0.8); the goodness of fit for simulations of N mineralization using these values were substantially worse than those shown in Fig. 7.

For the feed materials (Calliandra, Macrotyloma, poultry waste), the predictions were less good than for the faecal samples. To obtain a reasonable fit in the early stages of the mineralization a high C:N in FPOOL2 is required, but this results in very low values for FPOOL3 and over-prediction as the incubation period progresses beyond 100 days.

The resource quality factors that have been shown to influence N release from organic sources are the C:N ratio (or N concentration in plant materials for which C concentration varies little), lignin and polyphenol concentrations (Palm et al., 2001). These studies suggest that the effect of lignin is consistent with the concepts in the model in as much as higher lignin content can be represented by a greater proportion of the C in the slow decomposing pool. But it is also necessary to hypothesize that the FPOOLs differ in their C:N ratio. The polyphenol concentration in the materials studied by Delve et al. (2001) were low (<1.6%) except for the Calliandra feed. It remains uncertain how the effects of polyphenols on decomposition and N mineralization can be represented by the model.

Acknowledgements

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Dynamics of charge bearing soil organic matter fractions in highly weathered soils

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Abstract

Soil organic matter contributes significantly to cation exchange capacity, especially in highly weathered soils, where it can account for up to 90% of the total CEC of the topsoil. To determine how different amounts and qualities of plant residues affect the development of charge in these soils, we set out to (i) determine the effects of litter quality on the development of charge in soil and in its size separates and to (ii) determine the dynamics of this phenomenon in the field. For (i) we relied on a 20-year old arboretum where we collected soil samples under seven multipurpose tree species: *Afzelia africana, Dactyladenia barteri*, *Gliricidia sepium, Gmelina arborea, Leucaena leucocephala*, *Pterocarpus santalinoides*, and *Treculia africana*. For (ii) we installed decomposition tubes in the field with six treatments (control and *Afzelia, Dactyladenia, Gmelina, Leucaena* and *Treculia* at 15 Mg dry matter ha^{-1}) and followed the development of charge in the top 10 cm over a period of two years.

Samples from both experiments were dispersed by ultrasound and then physically fractionated by wet sieving and sedimentation. CEC measurements were made at 6 different pH values between 7.5 and 2.5 with the silver-thiourea method.

In the arboretum samples, carbon contents and CEC at in situ pH ranged between 7.16 and 13.62 g C kg^{-1} soil and between 2.8 and 6.5 cmol$_c$ kg^{-1} soil respectively. The clay and fine silt fractions were responsible for 76 to 90% of the soil CEC at pH 5.8. The contribution of the fine silt fraction to this CEC ranged from 35% to 50%. After 20 years, the fine silt reflected the treatment differences most clearly (Carbon: 34.1 – 65.8 g C kg^{-1} fraction and CEC: 16 - 36 cmol$_c$ kg^{-1} fraction at pH 6). The clay fraction seemed to be unaffected by the different organic inputs as it did not show clear differences in carbon content and CEC between treatments. Carbon content and pH together explained more than 85 % of the variation in CEC for the whole soil and the fractions. Differences in CEC between treatments could, as a consequence, be explained by the differences in carbon content. In total, SOM was responsible for 75 to 85% of the CEC of these soils.

The decomposition tube experiment revealed that after 23 months total soil carbon contents ranged between 3.8 and 5.3 g C kg^{-1} soil while CEC values at pH 5 (=average pH) ranged between 1.9 and 2.5 cmol$_c$ kg^{-1} soil. Fine silt carbon contents ranged between 18.3 and 26.5 g C kg^{-1} fine silt and CEC values at pH 5 varied between 5.3 and 8.9 cmol$_c$ kg^{-1} fine silt. Fine silt fractions again reflected the differences between the treatments most clearly, indicating that the lowest quality residues such as *Treculia* and *Dactyladenia* resulted in the largest CEC values and the largest carbon contents.

While the results from the first experiment confirm a role of low quality residues in the build-up of charge in weathered soils after 20 years, the second experiment indicates that even a single addition of these residues enhances charge characteristics significantly and for a significant length of time.

Key words: soil organic matter, charge characteristics, multipurpose trees, CEC, decomposition.

Introduction

The beneficial effects of soil organic matter management in the tropics have been amply documented as far as they relate to soil functions such as nutrient release (nitrogen and phosphorus in particular) and soil architecture (Vanlauwe et al., 1998; Nziguheba et al., 2000; Feller and Beare, 1997). Much less information is available on the relations between soil organic matter changes and the associated changes in nutrient retention capacity for neither cations nor anions. Nevertheless, soil organic matter is known to contribute to the total charge of a soil, a charge that is mostly pH-dependent. As a consequence, empirical relations do exist that predict soil cation exchange capacities based on soil organic carbon concentrations (Manrique et al., 1991; Asadu et al., 1997; Krogh et al., 2000). In highly weathered soils, the creation of extra charge, on top of the one derived from soil mineral components, can be an important management goal as CEC values can be increased by factors from values as low as 1 $cmol_c\ kg^{-1}$ soil to 4 - 6 $cmol_c\ kg^{-1}$ soil (Gallez et al., 1976; Oades et al., 1989). Apart from a general idea on soil organic matter dynamics, we do not have a precise idea on how fast we can positively affect charge characteristics and in which size fractions the impact is most strongly seen. In the present paper we present a dual approach. First, we will investigate the changes in charge brought about by a 20-year continuous input of tree litter of known quality in an attempt to relate litter quality with the ensuing changes in soil charge characteristics. Secondly, we will address an important and ensuing management issue in this that it is crucial to determine how fast the changes in charge come about by an input of litter of a given quality and also, how long lived these changes are.

Materials and methods

Site description

For the first part of the experiment, we relied on a 20-year old arboretum established in 1979 on a ferric Lixisol (WRB, 1998) at the International Institute of Tropical Agriculture (IITA) in Ibadan, South Western Nigeria (3°54'E and 7°30'N) where we collected soil samples under seven multi-purpose trees: *Afzelia africana, Dactyladenia barteri, Gliricidia sepium, Gmelina arborea, Leucaena leucocephala, Pterocarpus santalinoides* and *Treculia africana.* For more information on this site we refer to Oorts et al., (2000) and Kang and Akinnifesi (1994). We took soil samples in March 1999 from the surface horizons (0-10 cm) of the corresponding plots by taking 4 cores (10 cm depth, 10 cm dia) from each alley at random throughout the alley. Samples from different alleys were considered as field replicates. Litter was collected from the soil surface before soil sampling and leaves from the respective trees collected. Both litter and leaves were air dried before analysis. For the field incubation experiment, decomposition tubes (10 cm depth, 10.5 cm dia) were filled with topsoil (0-10 cm) of a ferric Lixisol (WRB, 1998) sampled at the I.I.T.A. campus and were installed in an adjacent plot. They were either kept bare or were amended with litter derived from *Afzelia*, *Dactyladenia*, *Gmelina*, *Leucaena* and *Treculia*. In the amended treatments soil was mixed with litter at an addition rate of 15 tons dry matter/ha in the top 10 cm of each core. Destructive sampling took place at 3, 6, 12 and 23 months after application. In both experiments, all soil samples were air-dried, and passed through a 4 mm sieve to remove roots and large stones before fractionation and analyses.

Fractionation

The soil organic matter fractions from the arboretum samples and decomposition tubes sampled at 6 and 23 months after application were obtained by size separation after ultrasound dispersion. To this end, soil suspensions (25g soil and 125 ml distilled water) were subject to a 10 minutes sonication treatment at 62.5 W (=1500 J g^{-1} soil) with Misonix Sonicator XL2020. The soil suspension so obtained was then separated into the following size classes: > 2 mm, 0.25-2 mm and 0.053 - 0.25 mm using wet sieving (Fritsch analysette 3, 50 Hz, 1.5 mm amplitude). The fractions on the sieve were collected and further split into mineral and organic components through flotation-decantation on water. Material smaller than 0.053 mm was collected and manually sieved through a 0.020 mm screen. The fine silt fraction (0.002 - 0.20 mm) was separated from a subsample by sedimentation (four cycles) and the clay fraction (< 0.002 mm) collected from the respective supernatants by flocculation with $CaCl_2$ (± 0.02 M). The clay fraction was next washed salt-free by dialysis (Spectra/Por 4, MWCO 12-14.000). All fractions were dried overnight at 60°C and weighed. The above separation scheme resulted in 9 fractions: 2-4 mm mineral (M2000), 2-4 mm organic (O2000), 0.250-2 mineral (M250), 0.250-2 organic (O250), 0.053-

0.250 mineral (M53), 0.053-0.250 organic (O53), 0.020-0.053 (coarse silt), 0.002-0.020 (fine silt) and < 0.002 (clay). Dry weight recoveries over the different samples ranged between 98.1 and 99.6 %.

Analyses

Soil pH was always measured in a 0.01 M $CaCl_2$ solution at a 1:5 soil:solution ratio after 1 h shaking. Organic carbon and nitrogen contents of soil and plant samples were determined using a CN analyser- mass spectrometer (ANCA-GSL preparation module and 20-20 Stable Isotope Analyser, Europa Scientific) after ball-milling. Plant material was analysed for lignin and (hemi)-cellulose content by the acid detergent method (Van Soest, 1963; Van Soest and Wine, 1967). Polyphenolics were determined by a revised Folin-Denis method (King and Heath, 1967). To account for the specifics of highly weathered soils, we used a CEC method designed to operate at in situ soil pH and at low ionic strengths. An unbuffered AgTU (silver-thiourea complex) solution (0.01 M Ag^+, 0.1 M TU) was used to measure CEC and base saturation at prevailing pH of the whole soil samples from the arboretum (Pleysier and Juo, 1980). Variation of CEC with pH was determined on whole soil samples and the three smallest size separates. In short, (a full description of the method is found in Oorts et al., 2000) subsamples were weighed in centrifuge tubes and pH was increased by shaking for 2 h with 15 ml 10^{-3} M NaOH. Next, 15 ml unbuffered AgTU (final concentration: 0.01 M Ag^+, 0.1 M TU) was added and after shaking overnight, pH was recorded, samples were centrifuged and a first 1 ml subsample was taken from the clear supernatant for Ag analysis by AAS. Subsequently, the soil was gradually acidified by adding small amounts of 1 M HNO_3 and after each equilibration, pH was measured and a subsample taken from the supernatant for Ag analysis. The whole procedure resulted for each sample in 6 CEC measurements between pH 2.5 and 7.5.

Results and discussion

Arboretum

Soils in the arboretum were predominantly sandy, with an approximate composition of 79% sand, 13% silt and 8% clay. The largest soil organic carbon concentrations were observed in the *Dactyladenia*, *Leucaena* and *Treculia* stands ranging between 10.79 and 13.62 g C kg^{-1} soil (Table 1). The four other soils had comparable and considerably lower carbon concentrations in a range of 7.16 to 7.97 g kg^{-1}. CEC values at prevailing soil pH ranged correspondingly between 4.51 and 6.47 $cmol_c$ kg^{-1} for the three top stands and between 2.80 and 3.90 $cmol_c$ kg^{-1} for the four others that were lower in carbon. Most of the variation in CEC could be explained by the differences in carbon content, while an additional part of the CEC variation was explained by the pH.

$CEC = 0.15 + 0.43* C\ (g\ kg^{-1})$ $n = 28, R^2 = 0.767, P<0.001$ (1)

$CEC = -6.97 + 1.25\ pH + 0.41*C\ (g\ kg^{-1})$ $n = 28, R^2 = 0.870, P<0.001$ (2)

Also when CEC values were obtained at different pH values, most of the variation could be explained by differences in organic carbon concentration and pH. These two together explained 85% of the variation.

$CEC = -1.79 + 0.50*pH + 0.36*C\ (g\ kg^{-1})$ $n = 168, R^2 = 0.849, P<0.001$ (3)

This allows concluding that in these soils the concentration of organic carbon is the main source of variation between the different treatments. The regressions between soil carbon content and CEC allowed calculating values for the CEC of the soil organic matter. From equation (1) it can be seen that values are obtained in the order of 430 ± 50 $cmol_c$ kg^{-1} C, at a pH of 5.8 which is the average in situ pH.

Fractions

The CEC of the coarse silt, fine silt and clay fractions increased with decreasing particle size (clay > fine silt > coarse silt), except for *Treculia*, *Dactyladenia* and *Leucaena*, where the fine silt had comparable or higher CEC values than the clay fractions. Clay and fine silt fraction had the highest contribution to the CEC of the whole soil, together they were responsible for 76 to 90% of the CEC of the soil at pH 5.8 (Table 2). The contribution of the fine silt fraction to the CEC at pH 5.8 ranged from 35% to 50%. For the soils under *Treculia* and *Dactyladenia*, this fine silt fraction had the highest contribution. The coarse silt fraction contributed 9 to 15% of the CEC. The recovery of the CEC in the fractions ranged from 95 to 104%. In Table 2, also the changes in organic carbon for the three main size separates are given. In general, the carbon concentrations of both silt fractions followed the same trends as the whole soil samples, with largest values for *Dactyladenia*, *Treculia* and *Leucaena*.

As for carbon, the treatment effects on CEC were clearly present in the silt fractions, while the clay fractions were rather similar (Figure 1). The CEC values for the clay fractions varied between 15 and 20 $\text{cmol}_c\ \text{kg}^{-1}$ at pH 3 and between 24 and 32 $\text{cmol}_c\ \text{kg}^{-1}$ at pH 7. The variation in CEC values for the clay fraction could be explained for 83% by pH only, confirming the absence of a treatment effect through the residue application on CEC values of the clay fraction. Contrary to this, the CEC values of the fine silt fraction were highly dependent on the treatment and pH could only explain 24% of the variation. Carbon concentration and pH together explained 95% of the variation in CEC of the fine silt fraction. The same was true for the coarse silt fraction: pH alone explained 18% of the variation and pH together with carbon concentration explained 90%. It confirms that changes in CEC due to residue management are seen in silt fractions rather than in clay fractions, at least at this time scale.

Decomposition tubes

Soil in the decomposition tubes had a similar sandy texture as the arboretum soils: 76% sand, 16% silt and 8% clay. The results in Table 3 show that due to the single application of residues, important differences in soil carbon content and CEC were obtained and still obvious after up to 23 months after application. After 6 months, the residue application resulted in an increase in total soil organic carbon content from 4.22 g C kg^{-1} soil in the control to concentrations up to 6.07 g C kg^{-1} soil in the soil amended with *Treculia*, six months after application. The change in organic carbon content was the largest for this species and decreased from *Treculia*>*Dactyladenia*>*Gmelina*>*Leucaena*>*Afzelia*. Correspondingly CEC values decreased from 2.75 $\text{cmol}_c\ \text{kg}^{-1}$ soil for the *Treculia* amendment to 2.07 $\text{cmol}_c\ \text{kg}^{-1}$ soil for *Afzelia*, only slightly larger than the 1.92 $\text{cmol}_c\ \text{kg}^{-1}$ soil for the control. The carbon concentrations in the fine silt fraction, six months after amendment, followed the same trend, while the largest values were obtained for *Dactyladenia* and *Treculia*, and the smallest for *Afzelia*. CEC values of the fine silt fraction could be separated into two groups: on the one hand *Treculia*, *Gmelina* and *Dactyladenia* with values between 10.49 and 10.66 $\text{cmol}_c\ \text{kg}^{-1}$ fine silt and on the other hand *Leucaena* and *Afzelia* with values of 8.76 and 8.41 $\text{cmol}_c\ \text{kg}^{-1}$ fine silt respectively. Still, all residue treated soils had larger CEC values in the fine silt fraction than the unamended soil with 7.89 $\text{cmol}_c\ \text{kg}^{-1}$ fine silt. Also for the clay fraction after six months, the organic matter concentrations seemed larger in the amended soils than in the control (values between 28.48 and 30.67 g C kg^{-1} clay for the amended soils and 25.48 g C kg^{-1} for the control). However, the CEC values were similar for treated and untreated soils in a range of 19.35 to 21.25 $\text{cmol}_c\ \text{kg}^{-1}$ clay. After 23 months, the effects were still present in some treatments, while a decrease in carbon concentrations was obvious, both in control and amended soils. For the whole soil, the same order as at 6 months was still visible with *Treculia* still displaying the largest carbon content (5.25 g C kg^{-1} soil) and *Afzelia* and *Leucaena* becoming similar as the control soil with carbon concentrations between 3.76 and 3.85 g C kg^{-1} soil. CEC values for the whole soil at 23 months were also still larger than the control for *Treculia* and *Gmelina*, while they were similar as for the control for *Leucaena*, *Afzelia* and *Dactyladenia*. Treatment effects could much more clearly be seen in the fine silt fraction. For *Treculia*, *Dactyladenia*, *Gmelina* and *Leucaena* values were observed between 20.60 and 26.49 g C kg^{-1} fine silt in contrast to the values of 18.57 and 18.26 g C kg^{-1} fine silt for the *Afzelia* and control soils respectively. Trends in CEC values of the fine silt fraction followed the lines set by the organic matter concentrations: larger values for the silt fractions derived from *Treculia* and *Dactyladenia* than for those obtained from *Gmelina* and *Leucaena*, in turn larger than for *Afzelia* which was no longer discernible from the control value. Not surprisingly, neither carbon concentrations nor CEC values were affected by the treatments in the clay fraction.

In general, the *Treculia* and *Dactyladenia* treatments were still displaying strong effects on soil organic carbon concentrations and ensuing CEC values of the total soil and its fine silt fraction in a time frame of up to 23 months after addition. *Gmelina* also produced similar effects, but definitely to a lesser extent. Referring to the quality of the different residues (Table 4), it becomes clear that the changes brought about in soil carbon and/or CEC are indirectly due to the differences in biochemical quality of the residues. *Dactyladenia* and *Treculia* had the lowest nitrogen contents and consequently the larger C/N ratios, predicting a slower decomposition and hence a larger residual carbon build-up. Both species also displayed the largest polyphenol concentrations, hence the largest polyphenol/N ratios, also pointing to slow decay rates. Lignin concentrations, however, were not in line with these observations.

The magnitude of the changes is significant and important in view of the generally small values obtained for both organic carbon contents and CEC values in this weathered Lixisol. An increase in carbon content and charge at in situ pH in the order of 20%, still observable, 23 months after a single addition of *Treculia* residues is a relevant result that may lead to the inclusion of such amendments in a realistic farming system. The phenomena were - as also indicated in earlier work (Oorts et al., 2000) - restricted to the fine silt fraction. Whether the absence of any effect in the clay fraction was due to a saturation of the clay fraction with organic matter or to the limited time frame (organic matter derived from the residue not yet sequestered in the clay fraction) could not be ascertained. Yet, the former possibility seems unlikely in this soil, strongly weathered and depleted in carbon. More likely seems the latter possibility confirming the slower turnover of organic components, as size of the soil particles with which they are associated becomes smaller.

Conclusion

Both parts of the experimental program confirm the strong relation between soil organic matter and charge development in highly weathered soils, such as the ferric Lixisol in Ibadan, Nigeria. In the soil derived from the arboretum, after 20 years of continuous input of litters widely ranging in nitrogen, lignin and polyphenol contents, large differences in organic matter resulted with concomitant large differences in CEC. Because differences in CEC could be explained almost completely by the variation in soil organic carbon concentration, the effect of residue inputs was judged indirect. Differences in CEC were due to changes in the silt fractions predominantly, indicating that changes in clay fractions are not readily obtained in a time-span of less than 20 years. The decomposition tube experiment was completely in line with the above findings in this that a low quality residue proved instrumental in enhancing charge in these soils. Yet it also demonstrated that such effects could be obtained already after a single addition of 15 Mg/ha and that they were still obvious almost two years after this addition.

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Table 1: Soil characteristics of the surface (0-10 cm) horizons of the selected plots in the Ibadan-arboretum.

Treatment	**C** g kg^{-1}	**N** g kg^{-1}	**pH**	**CEC** cmol$_c$ kg^{-1}	**Sand[†]** g kg^{-1}	**Silt** g kg^{-1}	**Clay** g kg^{-1}
Afzelia	7.68 ± 0.87[‡]	0.51 ± 0.08	6.3 ± 0.2	3.79 ± 0.30	817 ± 10	113 ± 9	58 ± 4
Dactyladenia	12.04 ± 2.26	0.75 ± 0.15	5.5 ± 0.2	4.51 ± 0.78	779 ± 21	127 ± 11	78 ± 10
Gliricidia	7.48 ± 0.61	0.61 ± 0.08	5.5 ± 0.1	3.03 ± 0.57	811 ± 19	112 ± 5	68 ± 17
Gmelina	7.97 ± 0.41	0.66 ± 0.06	6.1 ± 0.2	3.90 ± 0.52	785 ± 9	120 ± 7	71 ± 7
Leucaena	13.62 ± 1.92	1.26 ± 0.19	6.0 ± 0.1	6.47 ± 0.87	738 ± 29	138 ± 9	107 ± 22
Pterocarpus	7.16 ± 0.77	0.52 ± 0.07	5.5 ± 0.2	2.80 ± 0.44	797 ± 17	116 ± 3	79 ± 14
Treculia	10.79 ± 1.29	0.62 ± 0.07	5.8 ± 0.1	5.08 ± 0.84	798 ± 26	122 ± 7	68 ± 18

[†] sand: 0.053-2 mm, silt: 0.002-0.053 mm; clay: < 0.002 mm; [‡] average ± standard deviation of 4 replicates.

Table 2: Organic carbon content and contribution to the whole soil CEC at pH 5.8 of the particle size fractions of the surface (0-10 cm) horizons from the selected plots in the Ibadan-arboretum.

	Organic carbon (g C kg^{-1})			**CEC (cmol$_c$ kg^{-1} whole soil) at pH 5.8**		
Treatment	**Coarse Silt**	**Fine Silt**	**Clay**	**Coarse Silt**	**Fine Silt**	**Clay**
Afzelia	23.3 ± 6.9[†]	40.3 ± 5.5	37.1 ± 3.1	0.44 ± 0.04	1.42 ± 0.13	1.47 ± 0.04
Dactyladenia	28.1 ± 3.8	52.4 ± 6.9	36.5 ± 3.7	0.46 ± 0.09	2.15 ± 0.41	1.96 ± 0.29
Gliricidia	27.6 ± 2.2	36.2 ± 1.6	33.0 ± 2.3	0.41 ± 0.01	1.26 ± 0.09	1.63 ± 0.35
Gmelina	18.8 ± 1.2	37.8 ± 1.8	35.3 ± 5.3	0.38 ± 0.09	1.42 ± 0.17	2.05 ± 0.19
Leucaena	42.0 ± 8.5	56.3 ± 7.3	35.7 ± 5.6	0.76 ± 0.11	2.61 ± 0.23	2.95 ± 0.55
Pterocarpus	24.0 ± 4.6	34.1 ± 4.7	29.4 ± 3.1	0.34 ± 0.06	1.19 ± 0.17	1.82 ± 0.31
Treculia	46.1 ± 5.0	65.8 ± 5.2	34.7 ± 5.3	0.86 ± 0.08	2.84 ± 0.26	1.83 ± 0.37

[†] average ± standard deviation of 4 replicates.

Table 3: Carbon contents and CEC of the whole soil, fine silt and clay fractions of the different treatments after 6 and 23 months decomposition in the field.

Treatment	Whole soil C g kg^{-1}	 CEC at pH 5 cmol kg^{-1}	Fine Silt C g kg^{-1}	 CEC at pH 5 cmol kg^{-1}	Clay C g kg^{-1}	 CEC at pH 5 cmol kg^{-1}
6 Months						
Control	4.22	1.92	18.99	7.89	25.48	20.20
Afzelia	4.74	2.07	20.95	8.41	29.67	20.37
Dactyladenia	5.71	2.61	28.84	10.64	29.02	20.51
Gmelina	5.34	2.42	24.58	10.49	28.48	19.35
Leucaena	5.18	2.50	23.23	8.76	30.51	20.84
Treculia	6.07	2.75	27.80	10.66	30.67	21.25
23 Months						
Control	3.85	2.17	18.26	5.79	28.45	22.64
Afzelia	3.82	1.94	18.57	5.31	27.64	21.06
Dactyladenia	4.67	2.19	24.42	8.08	27.91	21.85
Gmelina	4.63	2.30	20.60	6.46	28.64	20.55
Leucaena	3.76	2.08	21.33	6.50	27.13	21.31
Treculia	5.25	2.53	26.49	8.94	26.65	21.89

Table 4: Biochemical composition of the leaf material from the different multipurpose trees in the selected plots in the Ibadan-arboretum.

Tree species	**C** **g kg^{-1}**	**N** **g kg^{-1}**	**Polyph** [†] **g kg^{-1}**	**Polyph/N**	**Lignin** **g kg^{-1}**	**Lignin/N**	**Cellulose** **g kg^{-1}**
Afzelia	467 ± 5 [‡]	38.2 ± 0.8	6.4 ± 0.6	0.17 ± 0.02	87 ± 3	2.3 ± 0.1	287 ± 14
Dactyladenia	457 ± 4	15.9 ± 0.3	67.0 ± 2.1	4.21 ± 0.13	195 ± 14	12.2 ± 1.1	238 ± 9
Gliricidia	453 ± 3	46.6 ± 0.7	22.8 ± 5.0	0.49 ± 0.11	53 ± 16	1.1 ± 0.4	196 ± 18
Gmelina	465 ± 2	29.1 ± 0.5	17.7 ± 1.8	0.61 ± 0.07	130 ± 19	4.5 ± 0.7	264 ± 43
Leucaena	455 ± 1	53.0 ± 0.2	85.4 ± 11.5	1.61 ± 0.21	51 ± 12	1.0 ± 0.2	126 ± 19
Pterocarpus	478 ± 2	33.3 ± 0.4	15.6 ± 2.5	0.47 ± 0.08	152 ± 6	4.6 ± 0.2	248 ± 19
Treculia	467 ± 3	21.9 ± 0.3	88.2 ± 7.8	4.03 ± 0.40	91 ± 9	4.1 ± 0.4	215 ± 15

† Polyph = Polyphenolics; ‡ average ± standard deviation of 4 replicates.

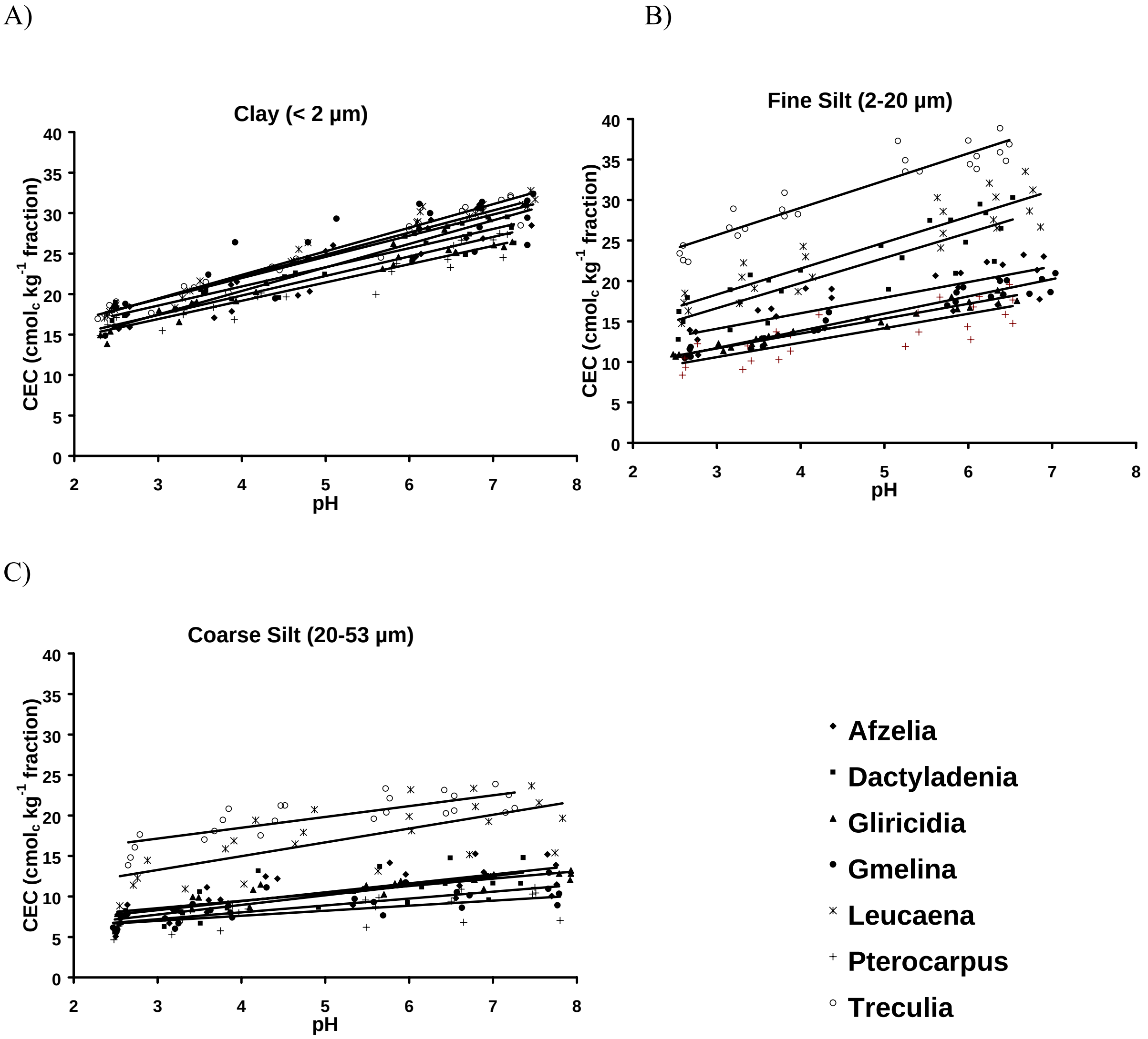

Figure 1: CEC versus pH for (A) clay fractions, (B) fine silt fractions and (C) coarse silt fractions derived from the 0-10 cm upper horizon from the selected plots in the Ibadan arboretum.

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Fertility status of soils of the derived savanna and northern guinea savanna and response to major plant nutrients, as influenced by soil type and land use management

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Keywords: fertilizer use, maize, missing nutrient trial, Olsen-P, on-farm level, particulate organic matter, pot experiment

Abstract

Although the fertility status of soils in the West African moist savanna is generally believed to be low, crop yields on farmers' fields vary widely from virtually nil to values near the potential production. The soil fertility status was evaluated for a number of farmers' fields selected at random in 2 villages (Zouzouvou and Eglimé) representative for the derived savanna (DS) benchmark area and in 2 villages (Danayamaka and Kayawa) representative for the Northern Guinea savanna (NGS) benchmark area. The relation between soil fertility status and soil type characteristics and fertilizer use was explored. In an accompanying missing nutrient greenhouse trial, the most limiting nutrients for maize growth were determined. While soils in the DS villages were formed on different geological units, soils in the NGS villages could be differentiated according to their position on the landscape. Generally, soils in the DS contained a smaller amount of silt (104 vs 288 g kg^{-1}), a larger amount of sand (785 vs 584 g kg^{-1}), C (9.3 vs 6.3 g kg^{-1}), N (0.7 vs 0.5 g kg^{-1}), Olsen-P (10.7 vs 5.4 mg kg^{-1}), and had a higher CEC (7.0 vs 4.8 cmolc kg^{-1}) than soils in the NGS villages. The large silt content of the soils in the NGS is a reflection of the aeolian origin of the parent material. Within the benchmark areas, general soil fertility characteristics were similar in the villages in the NGS, except for a larger amount of particulate organic matter in Kayawa than in Danayamaka. This may also have led to a significantly larger amount of ammonium-N content in the 0-20 and 20-40 cm soil layers in Kayawa compared to Danayamaka (42 vs 24 kg N ha^{-1} in the 0-20 cm soil layer). Differences in topsoil soil characteristics between the DS villages were a reflection of differences in clay quality (kaolinitic vs 2:1 clay minerals) of the parent material and past fertilizer use. The Olsen-P and exchangeable K contents were observed to increase with increased fertilizer application rate in both benchmarks, while fertilizer application rate had no significant effect on the organic C or total N content of the soil nor on its ECEC. The response of maize shoot biomass production to applied N was similar for both benchmarks (biomass accumulation in the treatment without N was, on average, 55% of the biomass production in the treatment which received all nutrients), while soils in the NGS responded more strongly to applied P than soils in the DS (37% vs 66% of biomass production in the treatment which received all nutrients). The more favourable P status of soils in Eglimé (DS) was attributed to the more intense use of P fertilizers, as a result of government-supported cotton production schemes. Response to cations, S or micronutrients were neglegible. A significant linear relationship was found between the soil Olsen-P content and the response to applied P up to levels of 12 mg kg^{-1} in the topsoil. Above this level, a plateau was reached.

Introduction

The fertility status of soils in the West African moist savanna is low. Two major causes are their extensive degree of weathering and the continuous mining of soil nutrients in the absence of sufficiently large amounts of external inputs or sufficiently long soil fertility-regenerating fallow periods (Jones and Wild, 1975; Smaling et al., 1997). In the absence of fertilizer additions, this low soil fertility status usually leads to very low maize grain yields on farmers' fields, e.g., around 0.75 t ha^{-1} in the Southern Benin Republic (Koudokpon et al., 1994), far below the potential yield of 5 – 8 t ha^{-1} (Fisher and Palmer, 1983). As P sorption by West-African savanna soils is low compared to soils of the humid forest zone (Juo and Fox, 1977), the most limiting nutrient for cereal production in the moist savanna is generally believed to be N, followed by P.

Since the early 1990s, research on natural resource management at the International Institute of Tropical Agriculture (IITA) has been following an agro-ecozonal approach. The West African moist savanna zone has been sub-divided into different agro-ecozones, each with their distinctive length of growing periods. Within each agroecozone, benchmark areas have been identified in which most of the IITA resource management research is concentrated (EPHTA, 1996). The benchmark area of the derived savanna (DS), with a growing period of 211-270 days (Jagtap, 1995), is located in Southern Benin Republic while the benchmark area of the northern guinea savanna (NGS), with a growing period of 151-180 days (Jagtap, 1995), is located in Northern Nigeria. As benchmark areas are hypothesized to contain all the biophysical and socio-economic variability found in the entire agro-ecozone, one could in principle extrapolate soil fertility management technologies developed and validated in the benchmark area to all of the agro-ecozone (EPHTA, 1996). A resource management survey implemented in the NGS benchmark led to the identification of 4 resource-use domains: a low (13.8% of survey villages), low to medium (49.2%), medium to high (23.1%), and high (13.8%) resource-use domain (Manyong et al., 1998). Resource use is quantified by an index taking into account variables describing use of external inputs, land use intensity, accessibility to markets, and diversification of the farm enterprise (Manyong et al., 1998).

Besides length of growing period and the socio-economic environment, soils also vary between and within the benchmark areas. In the DS benchmark, 2 main geological units can be distinguished, giving rise to distinct soil associations. In the southern part of the benchmark the predominant soils are deep, red, kaolinitic, freely draining soils developed on coastal sediments often referred to as 'Terre de Bare' and classified as Ferralic Nitisols (FAO, ISRIC and ISSS, 1998). The northern part is underlain by crystalline basement rocks consisting mainly of granite and gneiss, which gave rise to a complex pattern of Acrisols, Lixisols, Luvisols, and Leptosols with inclusions of Vertisols and Cambisols (Faure and Volkoff, 1998). The saprolite is often found within a few meters and the clay fraction contains kaolinite and swelling (2:1) clays in varying proportions according to parent rock and drainage conditions (Volkoff, 1976a; Volkoff, 1976b). A similar resource management survey as in the NGS was implemented in the DS benchmark. This identified a set of resource use domains overlapping with the geological units (IITA, 2000). In the DS benchmark, the production of cotton is supported by a credit scheme for fertilizers and herbicides and a government-regulated market for selling the produce (Bosc and Freud, 1995).

The soils in the NGS benchmark are predominantly developed in a Quaternary loess mantle which covered the Basement Complex granites, gneisses, migmatites and schists (Bennett, 1980; McTainsh, 1984). Processes of clay illuviation, iron segregation, fragmentation and horizontal transport of ironpans, and colluviation led to soil differentiation at the landscape scale. A typical toposequence consists of shallow and/or gravelly soils (Plinthosols or soils with a petroferric phase) on the interfluve crests, deeper soils (Luvisols or Lixisols) on the valley slopes and hydromorphic soils (Gleysols and Fluvisols or soils with gleyic properties) near the valley bottom (Delaure, 1998). As a common characteristic, these soils have a relatively high silt content (20-50%) reflecting the aeolian origin and have a clay fraction with low to medium activity (CEC of clay fraction between 20 and 35 $cmol_c$ kg^{-1} clay).

Agronomically, the most straightforward measure to boost cereal grain yields is the application of fertilizers. Although it is currently believed that both fertilizer and organic matter additions are necessary to sustain agricultural production and preserve the environment (Jones and Wild, 1975; Palm et al., 1997; Vanlauwe et al., 2000b), most farmers in the moist savanna do not apply organic matter except for minimal amounts of farmyard manure and/or household waste in the NGS (Houngnandan, 2000; Manyong et al., 2000). Crop residues are commonly removed from the field either for livestock feed and other purposes in the NGS or through burning in the DS. Although average fertilizer application by farmers in the DS as well as in the NGS is low (Houngnandan, 2000; Manyong et al., 2000), the range of application rates is high. In the NGS villages, the average fertilizer N application rate was 40 kg N ha^{-1} with a large standard deviation of 31 kg N ha^{-1} (Manyong et al., 2000).

The objectives of this paper were: (i) to assess the general soil fertility status of representative farmers' fields in a selected number of villages representative for the DS and NGS benchmarks, (ii) to assess the impact of soil type and fertilizer use on the selected soil characteristics, and (iii) to determine the most limiting nutrients for maize growth in the respective agro-ecozones and their relation with selected soil fertility characteristics.

Materials and methods

Village selection

As the NGS benchmark area is fairly homogeneous in terms of major soils associations, the 2 villages selected in the NGS were chosen to represent the major resource use domains identified by Manyong et al. (1998). Danayamaka (7°50'E, 11°19'N) belongs to the low to medium resource-use domain and is dominated by the traditional production enterprises of the northern Guinea savanna, such as sorghum, cowpea, and livestock. Kayawa (7°13'E, 11°13'N) belongs to the medium to high resource-use domain. It is characterized by the development of new enterprises such as maize and soybean, and follows a market-oriented strategy in agricultural production (Manyong et al., 1997). The two domains together encompass 72% of the villages surveyed in the NGS benchmark area.

As discussed earlier, in the DS benchmark 2 distinct geological formations are present, together covering 84% of the benchmark area (Volkoff, 1976a; Volkoff, 1976b). As the major soil characteristics were hypothesized to influence the soil fertility status of soils in this benchmark area, one village was selected belonging to each of the 2 soil associations. Zouzouvou (1°41'E, 6°53'N) lies on 'terre de barre' soils, while Eglimé (1°40'E, 7°05'N) is situated in the area underlain by crystalline rocks. The Eglimé soils are rejuvenated and much younger than the more weathered soils of Zouzouvou.

Socio-economic survey and farmers' field selection

A socio-economic survey on general farm characteristics and current use of fertilizer and organic inputs at the field level was implemented in the NGS (Manyong et al., 2000) and DS villages (Houngnandan, 2000). The farmers interviewed were selected following a multi-stage sampling procedure, giving a total number of 200 representative farmers in the NGS villages, and 171 in the DS villages (Houngnandan, 2000; Manyong et al., 2000). Of all fields included in the survey, 12-14 fields were randomly selected in each village to implement researcher-managed on-farm trials. In the NGS, soils near the valley-bottom or fadama soils were excluded from the selection procedure. The farmers using the selected fields were interviewed about past management of these fields. Information was obtained on cropping/fallow history and fertilizer use (type and amount) over the past 10 years.

Farmers' fields soil sampling and analysis

In all farmers' fields, trials were laid out containing 8 plots of 8 m by 8 m. In this paper, only the initial soil characteristics of the trials are considered; the trials themselves are the subject of forthcoming papers. Before implementation of the field trials, soil was sampled from each plot at 0-10 cm depth in April 1998 in the DS villages (one diagonal across the plots, 10 cores per plot) and in May and June 1998 in the NGS villages (both diagonals across the plots, 16 cores per plot). Afterwards, equal amounts of soil sampled from each of the 8 plots in a field were mixed to form one composite sample per field. All soil samples were air-dried and sieved to pass 4 mm. Part of the soil was ball-milled for organic C (Amato, 1983) and Kjeldahl-N analysis. A second part was analyzed for Olsen-P (Okalebo et al., 1993), effective cation exchange capacity (ECEC) (IITA, 1982), pH-water (soil:water ratio of 2.5), pH-KCl (soil:KCl solution ratio of 2.5), and texture (IITA, 1982). A third part was used to determine particle size classes of soil organic matter (SOM) by wet sieving a previously dispersed soil slurry over a nest of sieves (Vanlauwe et al., 1998). The particulate organic matter (POM) fraction consists of three separately measured SOM fractions: organic material larger than 2 mm (referred to as the 'O2000' fraction), organic material between 2 and 0.250 mm (referred to as the 'O250' fraction), and organic material between 0.250 and 0.053 mm (referred to as the 'O53' fraction).

Immediately after taking the soil samples from the 0-10 cm layer, sufficient soil was taken from the same layer from between the plots to implement a missing nutrient trial, described below. The soil was air-dried and sieved to pass 4 mm before use.

In the NGS villages, soil was sampled for mineral N extraction before planting maize in June 1998 (1 core in the centre of each plot bulked per field) at the following depths: 0-20 cm, 20-40 cm, 40-60 cm, and 60-80 cm. In the DS villages where a cowpea-maize rotation was implemented, soil was sampled at the same depths (2 cores per plot, bulked per field) after the cowpea harvest and before planting maize in August 1998. All samples were kept cool pending analysis. Mineral N was extracted by shaking 30 g fresh soil in 90 ml of a 2N KCl solution and filtering part of the supernatant after centrifugation of the soil slurry. The nitrate-N and ammonium-N content in the soil extract was determined colorimetrically on a continuous flow analyzer system (IITA, 1982).

Missing nutrient trial

A missing nutrient trial with soil sampled from all individual fields was established in the greenhouse at IITA, Ibadan, Nigeria. Pots were filled with 2.5 kg of air-dried, sieved soil and the treatments presented in Table 1 were implemented. After applying 75 ml of nutrient solution per pot, an additional 340 ml of distilled water was applied just before planting. Although the nutrient solutions were composed such that only the nutrients under consideration were missing - except for the 'all-N' treatment where Cl^- was added - the final pH (varied between 3.3 and 6.1) and electrical conductivity (varied between 0.9 and 2.4 dS m^{-1}) of the solutions were not equal. Preliminary testing, however, showed that after mixing a selected number of soils with the nutrient solutions, final soil pH values were hardly affected due to the buffering capacities of the soils (maximal differences in pH after applying the various nutrient solutions was 0.18 pH units for the selected soils). For the 'minus-N' treatment, a selected number of pots was also included with $CaCO_3$ as the Ca source rather than $CaCl_2$ to assess whether the addition of Cl^- had an effect on plant growth. As both Ca sources gave similar maize growth (data not shown), it was concluded that the addition of Cl^- did not affect maize growth. Although the differences in electrical conductivity of the nutrient solutions are the only factors besides the missing nutrients considered which could influence maize growth, the total salt concentrations were low (varied between 0.2 and 0.4 dS m^{-1} after applying the nutrient solutions to the soil as measured in a 1:2.5 soil:water suspension at 25°C) and as such, this factor was presumed not to influence maize growth.

The pots were arranged in a randomized complete block design with 3 replicates. After application of the nutrient solutions and distilled water, 4 maize seeds (variety Oba Super 2) were planted in each pot and thinned to 2 plants per pot after germination. The pots were watered twice daily thereby avoiding leakage of water through the bottom of the planting pots and avoiding signs of moisture stress on the maize plants. After 7 weeks, the maize plants were cut at the soil surface, oven-dried (65°C), and weighed. The roots were extracted from the soil by sieving over a 0.5 mm sieve, washed, oven-dried, and weighed.

Mathematical and statistical analyses

In the pot trial, the relative biomass production in the treatments with one or a range of nutrients removed vs the treatment with complete nutrition was calculated as (equation 1):

$$\frac{\text{Maize shoot or root biomass in the treatment with one or more missing nutrients}}{\text{Maize shoot or root biomass in the treatment with all nutrients applied}} * 100 \quad (1)$$

According to equation (1), a higher relative yield indicates a lower response to the missing nutrient considered.

The land use management, soil, and maize data were analyzed with the MIXED procedure of the SAS system (SAS, 1992) using ‘benchmark’ and ‘village within benchmark’ as fixed variables and ‘field*village within benchmark’ as a random factor. Significantly different means were separated with the PDIFF option of the LSMEANS statement.

To assess the impact of fertilizer use on the observed soil characteristics, the data were also analyzed using ‘benchmark’ and ‘fertilizer class’ as fixed variables and ‘field*fertilizer class within benchmark’ as a random factor. The ‘fertilizer class’ of a certain field was obtained by rounding the average of the ‘N fertilizer class’ and the ‘P fertilizer class’ values for that field. Three ‘N fertilizer classes’ were defined: I: > 60 kg N ha^{-1} yr^{-1}; II: 30-60 kg N ha^{-1} yr^{-1}, III: < 30 kg N ha^{-1} yr^{-1} and 3 ‘P fertilizer classes’ I: > 20 kg P ha^{-1} yr^{-1}; II: 10-20 kg P ha^{-1} yr^{-1}, III: < 10 kg P ha^{-1} yr^{-1} (Fig. 1). As fertilizer class was counfounded within village in the DS villages - nearly all the Zouzouvou soils belong to the class with the lowest fertilizer use, while nearly all Eglimé soils belong to the class with the highest fertilizer use (Fig. 1) – it was not possible to include both ‘village’ and ‘fertilizer class’ in the same ANOVA as certain factors were not estimable.

Regression analysis was used to calculate relationships between response to N and P and soil nutrient contents.

Results

Socio-economic characteristics of the villages studied

Fallows are still quite common in Zouzouvou (2.3 yrs per 10 yr) and virtually non-existent in all other villages (Table 2). In both benchmark areas, cereals are important crops, while more legume crops were grown during the past 10 yr in the DS villages. In the DS, cotton is a common cash crop, and in the NGS pepper and tomato are commonly grown. The type of NPK fertilizer commonly used is different in the two benchmarks. In the DS, cotton fertilizer (14%N, 23%P, 14%K, 5%S, 1%B) is virtually the only compound fertilizer available, and in the NGS several blends can be found, but 15:15:15 and 20:10:10 are the most common ones (Table 2).

While yearly N fertilizer application rates were not significantly different between the 2 benchmark areas, large differences in fertilizer use between the 2 villages in the DS benchmark were observed (Table 2). Farmers in Eglimé used, on average, 88 kg N ha^{-1} yr^{-1} for the past 10 years, and farmers in Zouzouvou used less than 10 kg N ha^{-1} yr^{-1}. Differences in fertilizer use between the 2 villages in the NGS were not significant. Farmers in the DS villages used significantly more P fertilizer (27 kg P ha^{-1} yr^{-1}) than farmers in the NGS villages (17 kg P ha^{-1} yr^{-1}), but again, striking differences in P use were observed between Zouzouvou (8 kg P ha^{-1} yr^{-1}) and Eglimé (45 kg P ha^{-1} yr^{-1}). In the DS, proportionally more N fertilizer was applied as urea in Eglimé than in Zouzouvou, and the same was true for Danayamaka in the NGS (Table 2).

Soil characteristics

While topsoils in the DS benchmark were generally more sandy and less silty than soils in the NGS benchmark, their organic C, total N, Olsen-P, exchangeable Ca and Mg contents and ECEC were significantly higher (Table 3). Soils in the DS contained more SOM particles with a higher particle size and soils in the NGS contained significantly more of the ‘O53’ material, leading to similar POM contents in both benchmarks (Table 3).

Although the soil chemical and organic matter characteristics of the 0-10 cm layer appeared to have larger values in Kayawa than in Danayamaka, none of the differences were significant, except for the O53 and POM content (Table 3). This is in sharp contrast with the DS villages, where topsoil in Eglimé contained a significantly larger amount of C, N, Olsen-P, exchangeable Ca, Mg, and K, and had a significantly higher ECEC. Topsoils in Eglimé also had a significantly lower sand and a significantly higher silt content than topsoils in Zouzouvou (Table 3). In the DS villages, nitrate-N and ammonium-N contents were similar for all soil depths, except for the 60-80 cm layers in which fields in Eglimé had significantly more ammonium-N than fields in Zouzouvou (Fig. 2a). The ammonium-N content in the 0-20 cm and 20-40 cm layers was significantly higher in Kayawa than in Danayamaka, while differences in nitrate-N content were similar at all soil depths (Fig. 2b). The soil profile contained more ammonium-N than nitrate-N in all soil layers and villages.

In both the DS and NGS villages, differences in soil organic C and total N content between fertilizer classes were not significant (Table 4). Olsen-P and exchangeable K contents, on the other hand, were significantly higher in class I than in class II or class III soils in both agro-ecozones. In the DS villages, exchangeable Ca and Mg contents were significantly higher in class I than in class III soils (Table 4). No significant differences in mineral N content of the soil profile were found between the different fertilizer classes (data not shown).

Missing nutrient pot experiment

The relative biomass yield of maize shoots in absence of N was similar for both benchmarks (Table 5). Soils in the NGS showed a lower relative shoot biomass yield in the absence of P than soils in the DS, indicating a stronger response to applied P (Table 5). In both benchmarks, responses to cations, S, and micronutrients were negligible. In the DS, maize shoot biomass responded more strongly to P in Zouzouvou than in Eglimé, while responses to N were similar in both villages. In the NGS, no differences in responses to N and P between villages were observed (Table 5).

Although a significant linear relationship was observed between shoot biomass response to N and the soil total N content, the relationship explained only 36% of the overall variation (Fig. 3a). This value decreases to 18% (significant at the 1% level) if the data point lying outside the cloud of points is omitted from the regression analysis. The relationships between shoot biomass response to P and Olsen-P contents followed a linear pattern up to about 12 mg Olsen-P kg^{-1}, after which responses tended to reach a plateau (Fig. 3b). The linear relationships between shoot biomass response to P and Olsen-P contents below 12 mg Olsen-P kg^{-1} explained between 60% and 74% of the overall variation for Zouzouvou, Danayamaka, and Kayawa. Slopes nor intercepts of the linear relationships were significantly different between these villages. Most of the Eglimé soils contained amounts of Olsen-P exceeding 12 mg P kg^{-1} and responses to P were part of the plateau of the relationship (Fig. 3b).

Discussion

The relative maize shoot biomass yield in absence of P was significantly smaller for soils from the NGS (relative yield of 33%) than from soils from the DS (67%), and within the DS, for soils from Zouzouvou (58%) than for soils from Eglimé (75%). The favourable P status in Eglimé soils is certainly caused by the extensive use of P-containing 'cotton' fertilizer, stimulated by the government-supported credit and marketing schemes for cotton production in Benin Republic. This observation is a good example of how agricultural policies may influence soil fertility status. Although the same policies apply to Zouzouvou, the lower fertilizer use in Zouzouvou compared to Eglimé may be explained by the lower occurrence of cotton (*data not shown*) and the lower inherent fertility of the soils caused by more intense weathering. Although 'cotton' fertilizer is usually applied to cotton, P fertilizer is known to have considerable residual effects on soils with low P sorption capacities (Bationo et al., 1986; Buresh et al., 1997), allowing other crops grown in rotation with cotton to benefit from this added P. Although use of P fertilizer is much lower in Zouzouvou than in Eglimé and comparable to P use in the NGS villages, the relative shoot biomass yield in absence of P is higher in Zouzouvou than in the latter villages. This may be related to differences in P sorption capacities of the A and Bt soil horizon between the soil profiles

(Nwoke et al., *unpublished data*). The higher P sorption of the NGS soils is most likely related to the greater amount of fine particles and the composition of these fine particles (Mokwunye et al., 1986). On the other hand, adulteration of locally produced fertilizer blends in the NGS can not be excluded and may have led to lower P application rates as calculated from the information given by the farmers.

The Olsen-P content appears to be a good indicator for P availability of West African moist savanna soils (Fig. 3b), as previously reported by Vanlauwe et al. (2000a). Soils containing Olsen-P values over 12 mg kg^{-1} are less likely to respond to applied P than soils with Olsen-P values below 12 mg kg^{-1}. For the latter soils, the response to P increased linearly with decreasing P content. Due to the high fertilizer application rates in Eglimé, little or no response to added P was observed for these soils. As 'cotton' fertilizer is the only commonly available compound fertilizer in Benin, one could wonder whether the composition of this fertilizer is agronomically and economically optimal for application to maize as maize is known to require relatively higher amounts of N than P (Wichmann, 1998).

Notwithstanding significant differences in soil organic C and total N content between benchmarks and, in the DS, between villages, responses to applied N were similar in all villages and benchmarks. Moreover, only a minor fraction of the total variation was explained by a linear relationships between response to N and soil total N content. These observations indicate that total C and N are weak indicators of potential soil N supply. Although inputs of organic matter are expected to be larger in the DS than in the NGS because of the longer growing period, fallow and crop residues are commonly burnt in the DS villages before planting the first season crop. In the NGS, fallow vegetation at the start of the cropping seasons is minimal and crop residues are commonly removed from the field for livestock feed, fencing, or other purposes. As belowground plant components and weeds are the major organic matter inputs, differences between benchmarks may not be as large as would be expected taking into account only the length of growing periods. This is also confirmed by the similar amounts of the easily available POM pool, which was shown to be rather easily influenced by application of fresh organic matter (Vanlauwe et al., 1999). As inputs of organic matter are expected to be in the same order of magnitude in both benchmarks, the larger C contents in the DS soils, and especially in Eglimé, indicate that in the DS, a higher proportion of the C is either physically and/or chemically protected from mineralization. This may be related to the more frequent burning of crop residues and consequent chemical stabilisation of C as charcoal in the DS villages. Physical protection of soil organic C is expected to be higher in the soils of the NGS villages due to their higher silt content and associated C protection capacity (Hassink and Whitmore, 1997). However, commonly used soil tillage practises may hamper the soil C protection mechanisms in contrast with the DS villages, where soils are usually only minimally tilled during weeding activities. Although the input of organic matter as above and belowground crop residues is expected to be larger in Eglimé than in Zouzouvou because of the much higher fertilizer application rates (Table 2), the frequent burning of crop residues and the higher silt content and associated C protection capacity (Hassink and Whitmore, 1997) in the Eglimé soils may mask the potentially higher N supply capacities of these soils. This is also obvious from the similar amounts of mineral N in the soil profile before maize planting. The larger amounts of mineral N in the topsoil in Kayawa compared with Danayamaka are likely the results of a larger amount of easily decomposable POM (Table 3).

The response to missing cations, S, and micronutrients was virtually nil in all fields, indicating that these nutrients are not an immediate source of concern. However, applying higher rates of N and P fertilizer may more rapidly exhaust the soil reserves of these nutrients and lead to other major deficiencies. Especially 'terre de barre' soils, which have an inherently low available K content, as confirmed by the data presented in Table 3, may be susceptible to K deficiency when agricultural production increases (Jones and Wild, 1975). On the other hand, as long as local fertilizer recommendation schemes include application of K fertilizer (Carsky and Iwuafor, 1999) and as farmers usually apply NPK fertilizers, this possibility may turn out to be a rather theoretical one.

Certain differences in soil characteristics between villages within one benchmark area are surely rather the result of inherent soil type characteristics than of management practices. The higher base status and silt content of the Eglimé soils compared with the Zouzouvou soils, e.g., is related to the higher base content of the parent material rather than to the use of external inputs. After all, the Eglimé soils are rejuvenated and much younger than the more weathered soils of Zouzouvou. The high silt content of the soils in the NGS villages reflects the aeolian origin of the parent material, formed by deposition of loess-like material by Harmattan winds (Bennett, 1980). Through this dust deposition, the soils in the NGS are enriched with bases at an annual rate of 19 kg K ha^{-1}, 10 kg Ca ha^{-1}, and 4 kg Mg ha^{-1} (McTainsh, 1982). Dust deposition decreases from North to South, and annual enrichment rates in the DS are of the order of 3 kg K ha^{-1}, 5 kg Ca ha^{-1}, and 2 kg Mg ha^{-1} (Hermann, 1996, cited by Stahr et al., 1996). Other differences in soil characteristics are more likely brought about by differences in soil management and particularly fertilizer use. Although one could argue that in the DS the larger P and K content of soils belonging fertilizer class I compared with soils belonging to fertilizer classes II and III is caused by the fact that fertilizer classes and soil type are confounded (most Eglimé soils belong to class I, while most Zouzouvou soils belong to class III), similar observations were made for fertilizer classes in the NGS, where soil types are similar (Table 4). This clearly shows that application of external sources of P and even K can improve the general P and K status and benefit future crops. This is not true in the case of N fertilizers, as neither the soil total N content nor the mineral N content in the soil profile varied between fertilizer classes (Table 4). One consequence of this observation is that N fertilizers need to be applied yearly to sustain crop growth. While it is often claimed that excessive long-term use of N fertilizers may decrease the soil pH, it is worth noting that topsoil pH values are similar for Zouzouvou and Eglimé (Table 4), while the difference in average yearly N fertilizer application is substantial (Table 2). This indicates that the acidifying activity is not relevant for all fertilizers. (Juo et al., 1995) already found that the acidifying effect of N fertilizer was highest for ammonium sulphate, lower for urea and virtually absent for calcium-ammonium-nitrate.

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Table 1: Composition of the different nutrient solutions applied in the nutrient omission pot experiment[a].

	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5
	complete	minus-N	minus-P	minus-cations/S	minus-micro-nutrients
	mmol l^{-1}				
Macronutrients					
NH_4NO_3	100.2	--	111.9	146.1	100.2
$NH_4H_2PO_4$	22.6	--	--	22.6	22.6
KNO_3	22.7	--	22.7	--	22.7
$Ca(NO_3)_2.4H_2O$	35.0	--	35.0	--	35.0
$MgSO_4.7H_2O$	21.9	21.9	21.9	--	21.9
KH_2PO_4	--	22.6	--	--	0
$CaCl_2.2H_2O$	--	35.0	--	--	0
Micronutrients					
$FeCl_3$	0.84	0.84	0.84	0.84	--
$MnCl_2.4H_2O$	0.54	0.54	0.54	0.54	--
$ZnCl_2$	0.72	0.72	0.72	0.72	--
$CuCl_2.2H_2O$	0.58	0.58	0.58	0.58	--
$Na_2B_4O_7.10H_2O$	0.057	0.057	0.057	0.057	--
$Na_2MoO_4.2H_2O$	0.037	0.037	0.037	0.037	--
$CoCl_2.6H_2O$	0.043	0.043	0.043	0.043	--
Macroelements					
N	316	0	316	316	316
P	23	23	0	23	23
K	23	23	23	0	23
Ca	35	35	35	0	35
Mg	22	22	22	0	22
S	22	22	22	0	22

[a] All pots received 75 ml of the respective nutrient solutions and 340 ml of distilled water at planting.

Table 2: General cropping system and soil fertility management characteristics of the different fields in the derived savanna and the northern guinea savanna benchmark villages[a].

	Derived savanna			Northern Guinea savanna			SE (village) (*n*=12)	SE (benchmark) (*n*=24)
	Zouzouvou	Eglimé	Mean	Danayamaka	Kayawa	Mean		
Cereals[b]	Maize			Maize, sorghum, (rice), (millet), (sugarcane)				
Legumes[b]	Cowpea, groundnut, (soybean)			Soybean, cowpea, (groundnut)				
Other important crops	Cotton			Pepper, tomato				
Common NPK fertilizer	'Cotton fertilizer' (14N:23P:14K:5S:1B)			15:15:15, 20:10:10				
Cereal crops in last 10 yrs	8	4	6	6	7	7	1	1
Legume crops in last 10 yrs	6	6	6	2	3	2	1	1
Fallow years in last 10 yrs	2.3	0.3	1.3	0.3	0.0	0.1	0.5	0.3
Yearly N use (kg ha^{-1} yr^{-1})	8	88	48	54	34	44	8	5
Yearly P use (kg ha^{-1} yr^{-1})	8	45	27	14	20	17	4	3
Yearly K use (kg ha^{-1} yr^{-1})	5	28	16	14	19	17	3	2
Proportion of N fertilizer as urea (%)	22	69	46	56	32	44	6	5

[a] Derived savanna: Zouzouvou and Eglimé (12 fields each); northern guinea savanna: Danayamaka (14 fields) and Kayawa (13 fields).

[b] Crops in parentheses are less commonly grown

Table 3: Selected soil (0-10 cm) chemical and physical of the fields in the derived savanna and the northern guinea savanna benchmark villages[a].

	Derived savanna			Northern Guinea savanna			SE (village) (*n*=12)	SE (benchmark) (*n*=24)
	Zouzouvou	Eglimé	Mean	Danayamaka	Kayawa	Mean		
Chemical characteristics								
Organic C (g kg^{-1})	7.9	10.7	9.3	5.5	7.1	6.3	0.6	0.4
Total N (g kg^{-1})	0.62	0.78	0.70	0.46	0.53	0.49	0.04	0.03
C-to-N ratio	12.9	13.6	13.2	12.2	13.5	12.9	0.5	0.3
Olsen-P (mg kg^{-1})	8.1	13.3	10.7	5.1	5.8	5.4	1.3	0.9
Ca^{2+} content ($cmol_c$ kg^{-1})	2.80	6.78	4.79	2.24	3.52	2.88	0.64	0.45
Mg^{2+} content ($cmol_c$ kg^{-1})	0.94	1.65	1.30	0.66	0.65	0.66	0.15	0.11
K^+ content ($cmol_c$ kg^{-1})	0.15	0.38	0.27	0.32	0.32	0.32	0.03	0.02
Exch. acidity ($cmol_c$ kg^{-1})	0.58	0.40	0.49	0.67	0.77	0.72	0.09	0.06
ECEC[b] ($cmol_c$ kg^{-1})	4.61	9.38	7.00	4.10	5.48	4.79	0.81	0.57
pH(H_2O)	6.7	6.7	6.7	6.1	6.0	6.0	0.1	0.1
pH(KCl)	5.1	5.3	5.2	4.9	4.9	4.9	0.2	0.1
Physical characteristics								
Gravel content (g kg^{-1})	0	19	10	6	2	4	3	2
Sand content (g kg^{-1})	834	736	785	606	562	584	20	14
Silt content (g kg^{-1})	61	147	104	276	300	288	12	9
Clay content (g kg^{-1})	105	117	111	118	138	128	14	10
Soil organic matter								
O2000 fraction (g kg^{-1})	0.12	0.07	0.09	0.04	0.04	0.04	0.01	0.01
O250 fraction (g kg^{-1})	0.20	0.19	0.19	0.16	0.19	0.17	0.02	0.01
O53 fraction (g kg^{-1})	0.25	0.29	0.27	0.31	0.44	0.38	0.04	0.03
POM[b] (g kg^{-1})	0.57	0.54	0.55	0.51	0.68	0.59	0.06	0.04

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[a] Derived savanna: Zouzouvou and Eglimé (12 fields each); northern guinea savanna: Danayamaka (14 fields) and Kayawa (13 fields).

[b] ‘ECEC’: ‘Effective Cation Exchange Capacity’; ‘POM’: ‘Particulate Organic Matter’

Table 4: Selected soil (0-10 cm) characteristics of the fields in the derived savanna and the northern guinea savanna benchmark villages as affected by fertilizer application[a].

	Derived savanna			Northern Guinea savanna			Minimal SED[c]	Maximal SED[c]
	Class I	Class II	Class III	Class I	Class II	Class III		
Chemical characteristics								
Organic C (g kg^{-1})	10.1	7.8	8.8	6.3	5.5	6.9	1.0	2.2
Total N (g kg^{-1})	0.75	0.60	0.67	0.45	0.46	0.53	0.07	0.15
C-to-N ratio	13.5	12.9	13.0	14.9	12.2	12.9	0.7	1.6
Olsen-P (mg kg^{-1})	13.3	9.8	8.6	10.3	4.5	5.0	1.8	4.1
Ca^{2+} content ($cmol_c$ kg^{-1})	6.30	4.25	3.62	2.97	2.24	3.36	1.01	2.31
Mg^{2+} content ($cmol_c$ kg^{-1})	1.56	1.30	1.08	0.77	0.65	0.65	0.23	0.52
K^+ content ($cmol_c$ kg^{-1})	0.38	0.20	0.18	0.47	0.31	0.29	0.05	0.10
Exch. acidity ($cmol_c$ kg^{-1})	0.42	0.30	0.58	0.70	0.61	0.82	0.12	0.28
ECEC[b] ($cmol_c$ kg^{-1})	8.8	6.2	5.6	5.1	4.0	5.3	1.3	2.9
pH(H_2O)	6.7	7.0	6.7	6.1	6.0	6.0	0.2	0.4
pH(KCl)	5.3	5.5	5.1	5.0	4.9	4.9	0.2	0.5
Soil organic matter								
O2000 fraction (g kg^{-1})	0.053	0.072	0.132	0.045	0.036	0.042	0.013	0.031
O250 fraction (g kg^{-1})	0.178	0.155	0.208	0.208	0.157	0.179	0.021	0.047
O53 fraction (g kg^{-1})	0.273	0.259	0.271	0.405	0.318	0.417	0.059	0.135
POM[b] (g kg^{-1})	0.503	0.465	0.611	0.658	0.509	0.637	0.083	0.189

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[a] Fertilizer classes for N application are: I: > 60 kg N ha^{-1} yr^{-1}; II: 30-60 kg N ha^{-1} yr^{-1}, III: < 30 kg N ha^{-1} yr^{-1}. Fertilizer classes for P application are: I: > 20 kg P ha^{-1} yr^{-1}; II: 10-20 kg P ha^{-1} yr^{-1}, III: < 10 kg P ha^{-1} yr^{-1}. Overall fertilizer classes, used in the column headings of this table, are the average of the values obtained for N and P fertilizer

[b] 'ECEC': 'Effective Cation Exchange Capacity'; 'POM': 'Particulate Organic Matter'

[c] The minimal and maximal Standard Errors of the Difference (SED) are given because each means comparison has a different number of degrees of freedom.

Table 5: Response[a] to missing nutrients of the different fields in the derived savanna and the northern guinea savanna benchmark villages[b]. Values nearer to 100% indicate less response to the missing nutrient(s) considered.

	Derived savanna			Northern Guinea savanna			SE (village) (*n*=12)	SE (benchmark) (*n*=24)
	Zouzouvou	Eglimé	Mean	Danayamaka	Kayawa	Mean		
	% of complete nutrition							
Shoot dry matter								
N	53.6	60.2	56.9	51.9	52.2	52.0	3.1	2.2
P	58.0	74.6	66.3	39.9	34.1	37.0	5.3	3.7
Ca, Mg, K, S	94.4	101.1	97.8	90.8	96.0	93.4	2.9	2.1
Micro[c]	96.0	96.9	96.5	98.1	94.5	96.3	3.2	2.3
Root dry matter								
N	71.3	92.1	81.7	81.3	77.7	79.5	5.5	3.9
P	61.4	87.6	74.5	43.2	31.9	37.6	6.2	4.4
Ca, Mg, K, S	81.4	104.5	93.0	96.0	95.1	95.5	4.8	3.4
Micro[a]	105.6	121.3	113.4	100.9	106.4	103.6	5.0	3.6

[a] Proportion of shoot and root biomass in the treatment with one or more missing nutrients over shoot and root biomass in the treatment which was given all nutrients.

[b] Derived savanna: Zouzouvou and Eglimé (12 fields each); northern guinea savanna: Danayamaka (14 fields) and Kayawa (13 fields).

[c] 'Micro' indicates missing micronutrients (Fe, Mn, Zn, Cu, B, Mo, Co).

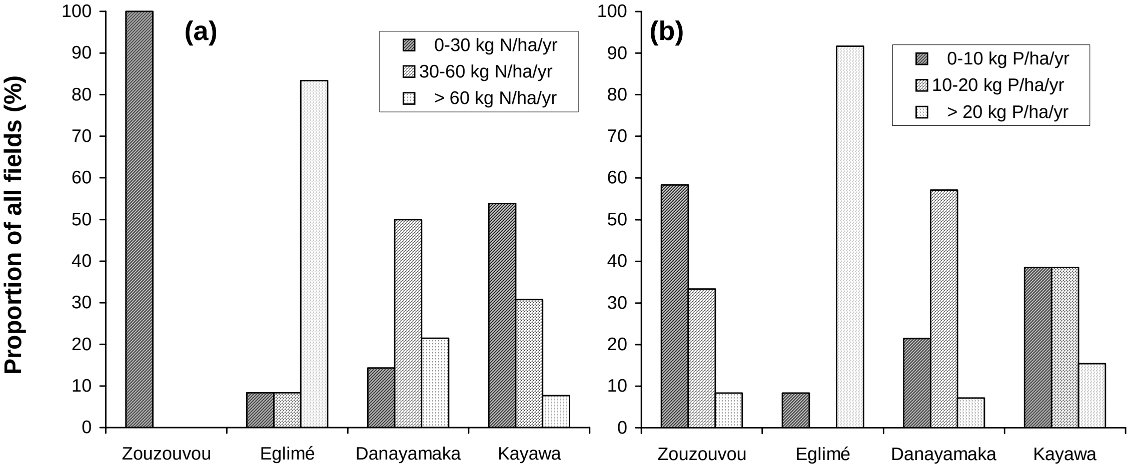

Fig. 1: Proportion of farmers' fields belonging to the various (a) N and (b) P fertilizer classes in the derived savanna benchmark villages (Zouzouvou and Eglimé) and in the northern guinea savanna benchmark villages (Danayamaka and Kayawa).

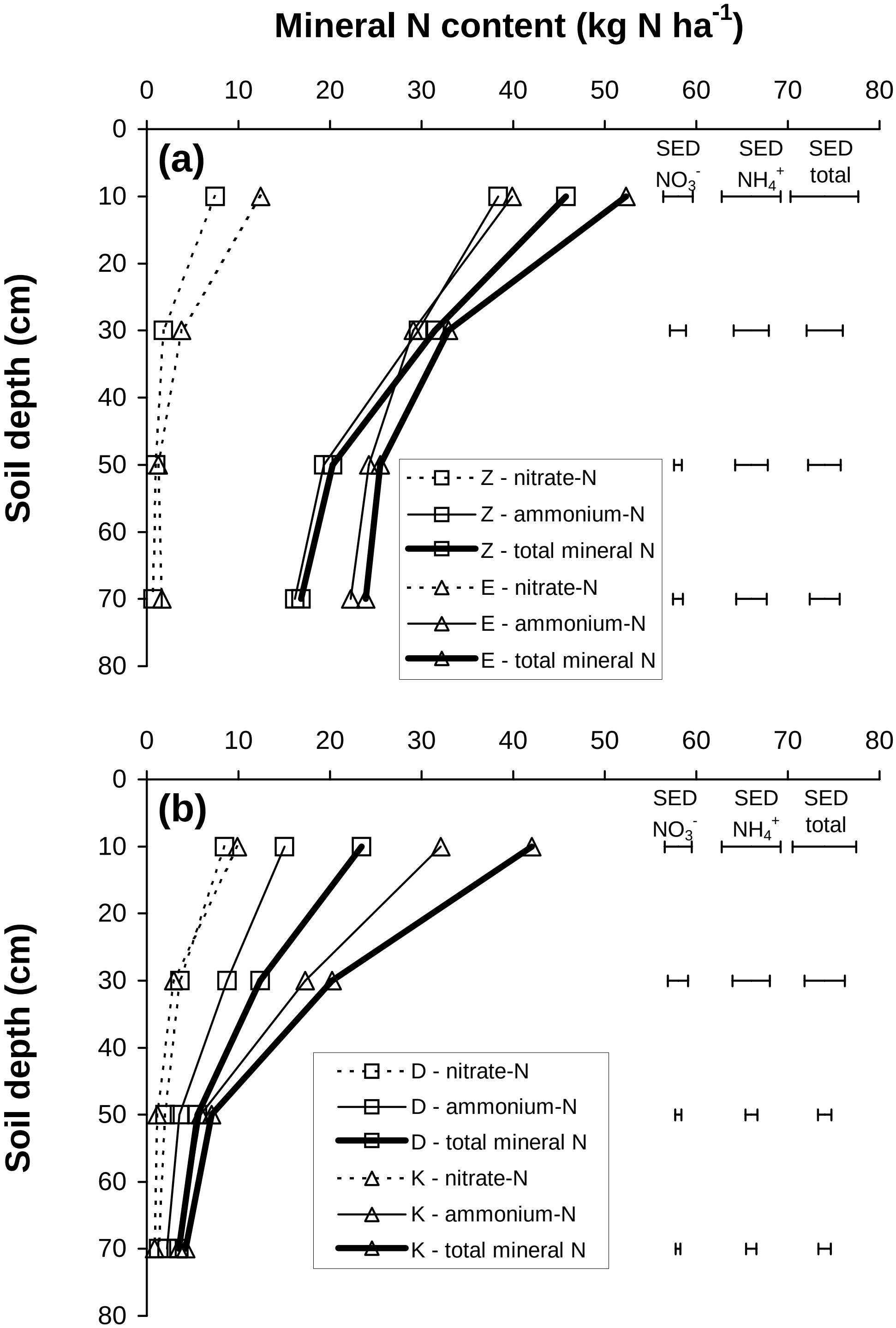

Fig. 2: Nitrate, ammonium, and total mineral N content in the soil profile in (a) the derived savanna benchmark villages (‘Z’ = Zouzouvou; ‘E’ = Eglimé) and (b) in the northern guinea savanna benchmark villages (‘D’ = Danayamaka; ‘K’ = Kayawa). ‘SED’ = Standard Error of the Difference.

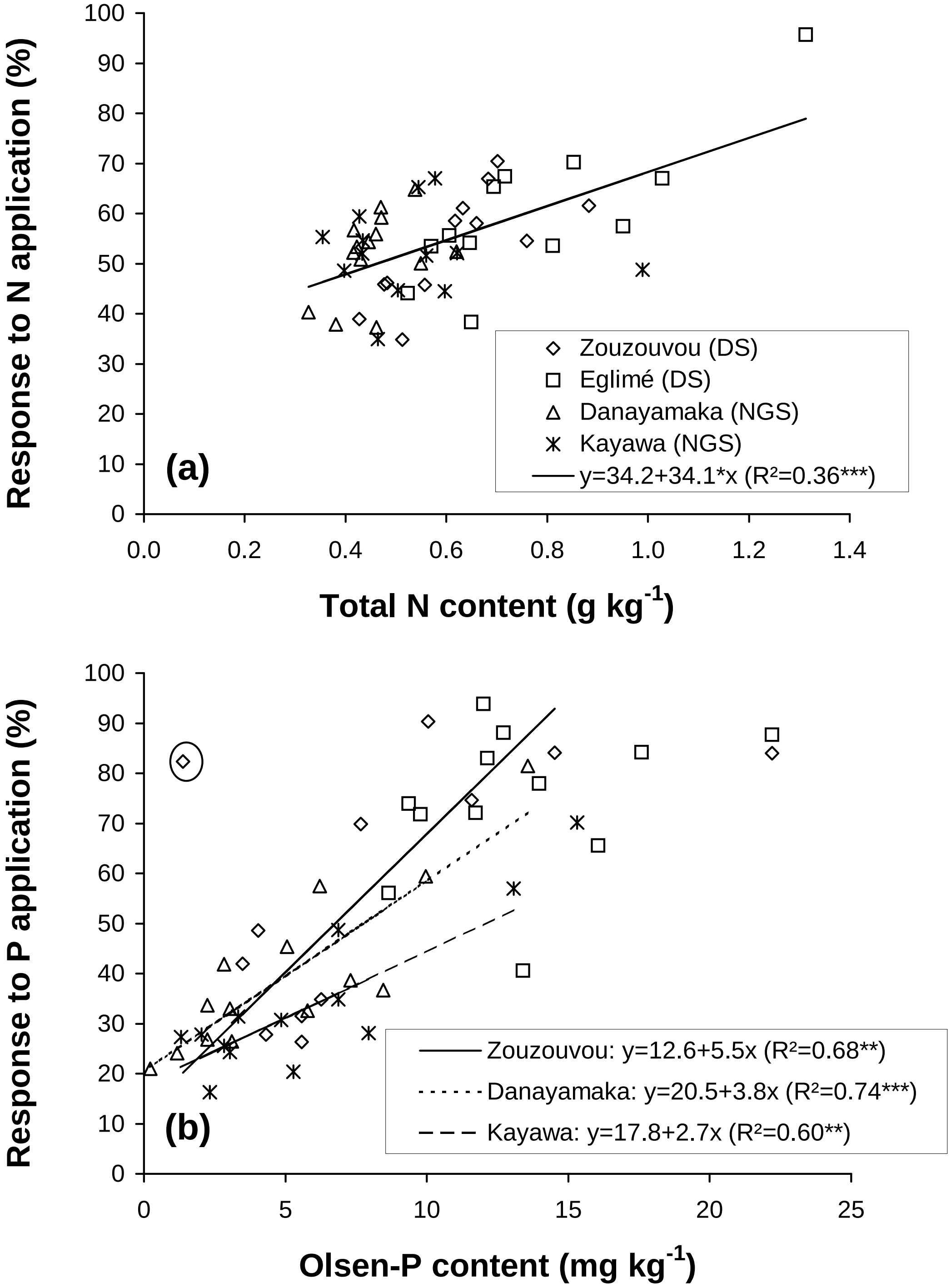

Fig. 3: Relationships between (a) the response to N and the soil total N content and (b) between the response to P and the soil Olsen-P content in a greenhouse pot experiment. The response is expressed as relative shoot biomass yield in the treatments with one or more missing nutrients relative to the treatment receiving all nutrients. As such, values closer to 100% indicate a lower response. 'DS' = derived savanna; 'NGS' = northern guinea savanna. The value encircled in Fig. 3b was excluded from the regression analysis.

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Root distribution of Senna siamea grown on a series of soils representative for the derived savanna zone in Togo, West Africa

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***Keywords**: alley cropping, root abundance, root length density, root weight density, tap root*

Abstract

Although crucial for assessing the functioning of alley cropping systems, quantitative information related to the hedgerow tree root distribution remains scarce. Soil mapping and destructive soil sampling was used to assess the impact of soil profile features on selected root characteristics of Senna siamea hedgerows, growing in alley cropping systems in three sites (Glidji, Amoutchou, and Sarakawa) representative for the derived savanna of Togo, West Africa. While the soil profiles in Glidji and Sarakawa contained a clay accumulation horizon, the Amoutchou profile was sandy up to 1 m. The number of small roots (diameter < 2 mm), quantified on a soil profile wall, decreased with depth in all sites. For most soil depths, the abundance of small roots tended to be higher near the tree base, e.g., ranging from 5.3 dm^{-2} in Amoutchou to 21.4 dm^{-2} in Glidji for the 0-20 cm layer, than in the middle of the alley, e.g., ranging from 3.1 dm^{-2} in Amoutchou to 13.8 dm^{-2} in Glidji for the 0-20 cm layer. Root length density (RLD) of the 0-10 cm and 10-20 cm layers was significantly higher in Glidji than in Amoutchou ($P < 0.05$) and in Sarakawa ($P = 0.08$). Differences in RLD between sites were not significant for layers below 30 cm. For each layer, root weight densities (RWD) were similar in all sites, e.g., ranging from 0.44 mg cm^{-3} in Amoutchou to 0.64 mg cm^{-3} in Glidji in the 0-10 cm layer, indicating that the roots in the Glidji topsoil had a smaller overall diameter than in Amoutchou. In Amoutchou, the relative RLD was lower than in Glidji or Sarakawa for the top 40 cm of soil, while the inverse was observed for the layers between 50 and 100 cm deep and this was related to the sandy soil profile in Amoutchou. Another consequence of the sandy profile was the larger tap root diameter below 50 cm in Amoutchou compared to Sarakawa. For all sites, significant ($P < 0.001$) linear regressions were observed between RLD's, RWD's, and the abundance of small roots, although the variation explained by the regression equations was highest for the relationship between RLD and RWD. The potential of the hedgerows to recover nutrients leached beyond the reach of food crops or the safety-net efficiency was evaluated for the tree sites.

Introduction

Several of the unresolved questions related to alley cropping in particular and agroforestry systems in general are associated with the root dynamics of the tree component. In alley cropping systems, 'ideal' hedgerows recover soil N and other nutrients only from layers below the rooting depth of the accompanying food crop. By doing so, trees recover nutrients leached beyond the reach of annual food crops and thus improve nutrient use efficiencies. Real-world hedgerows recover a substantial proportion of their nutrients from layers simultaneously exploited by food crop roots and increase competition in favor of the trees. To assess possible belowground competition for water and nutrients between the trees and associated food crops, data on root abundance as a function of soil depth, soil characteristics, and time are needed (Schroth, 1995; Van Noordwijk and Purnomosidhi, 1995).

Senna siamea Irwin & Barneby is a non-N_2-fixing leguminous tree which is commonly found in natural fallows in the moist savanna zone of West-Africa. *Senna* has been widely used in alley cropping trials (Ruhigwa et al., 1992; Danso and Morgan, 1993; Van der Meersch et al., 1993; Schroth and Lehmann, 1995; Aihou et al., 1999; Tossah et al., 1999; Vanlauwe et al., 2001a) or other agroforestry systems (Leihner et al., 1996) in West-Africa. Tossah et al. (1999) reported annual *Senna* aboveground biomass productions of 9.2, 1.8, and 9.8 ton ha^{-1}, in Glidji (Southern Togo) on a Rhodic Ferralsol, in Amoutchou (Central Togo) on a Haplic Arenosol, and in Sarakawa (Northern Togo) on a Ferric Acrisol, respectively. Although *Senna* has been depicted as an aggressive scavenger for nutrients due to its laterally spreading root system (Hauser, 1993), Aihou et al. (1999) and Tossah et al. (1999) concluded that *Senna* trees rely mainly on the subsoil as a source of nutrients. While Vanlauwe et al. (2001a) found only a small recovery of applied ^{15}N-urea in the *Senna* hedgerow during intercropping with maize on a non-acid Alfisol, Ruhigwa et al. (1992) concluded that *Senna* would compete for nutrients with the associated food crop in alley cropping systems, as most of its fine root biomass was confined to the top 20 cm of an acid Ultisol. Schroth et al. (1995) stated that the lateral development of *Senna* roots was favoured by the shallow soil depth on a Ferric Acrisol in Central Togo. Akinnifesi et al. (1995) found significant decreases in root length densities of *Enterolobium cyclocarpum* and *Leucaena leucocephala* with increases in soil bulk density. Above observations clearly indicate possible interactions between soil chemical and physical conditions on the one hand and the root distribution and competitive character of *Senna* trees on the other hand.

The objectives of this paper were (i) to quantify the root distribution of *Senna* hedgerows, growing in alley cropping systems on a number of sites representative for the derived savanna of Togo, (ii) to evaluate the effect of soil profile characteristics on the observed root distributions, (iii) to assess the potential of *Senna* trees to recover nutrients leached beyond the reach of food crops or the so-called safety-net efficiency, and (iv) to explore relationships between the different methods used to quantify root distributions.

Materials and methods

Site and soil characteristics and establishment of the alley cropping trials

The trials were established on a Rhodic Ferralsol in Glidji (Southern Togo – 6°15'N, 1°36'E), on a Haplic Arenosol in Amoutchou (Central Togo – 7°22'N, 1°10'E), and on a Ferric Acrisol in Sarakawa (Northern Togo – 9°37'N, 1°01'E). The present soil types represent about 57% of the soils in the DS (Jagtap, 1995). All sites are located in the Derived Savanna (DS) zone, which is characterized by a length of growing period between 211 and 270 days (Jagtap, 1995). Total rainfall in Glidji was 950 mm in 1995 and 876 mm in 1996 (bimodal pattern), in Amoutchou 1540 mm in 1995 and 1250 mm in 1996 (unimodal pattern), and in Sarakawa 1357 mm in 1995 and 1289 mm in 1996 (unimodal pattern). The site in Amoutchou had a groundwater table between 0.8 and 1.4 m below the soil surface, while the groundwater table of the others sites is deeper than 10 m.

The trials were established in 1991 in Glidji and in 1992 in Amoutchou and Sarakawa. A randomized complete block design with four replicates was laid out with five treatments consisting of four alley cropping plots and a no-tree control treatment. Plot size was 10 by 12 m and the hedges were planted at 4 m distance, making 3 10-m-long hedges per plot. The *Senna* seeds used in the three sites were collected from a *Senna* fallow near Lomé, Togo. In Glidji, the *Senna* trees were pruned 3 times yearly (before planting around mid-April, about 5 weeks after planting, and about 11 weeks after planting) in 1992 and again in 1994, 1995, and 1996 at 0.25 m above the soil surface while in Amoutchou and Sarakawa, the *Senna* trees were pruned 3 times in 1995 and 1996 (Tossah et al., 1999). During the years in which the trees were pruned, maize was planted at a distance of 80 (between rows) by 30 cm (within rows) and thinned to one plant per pocket. A basal application of 26 kg P ha^{-1} as TSP and 50 kg K ha^{-1} as KCl was applied to the maize at planting follwed by two applications of 22.5 kg N ha^{-1} of urea approximately 3.5 and 7.5 weeks after planting.

Quantification of selected root characteristics and soil sampling

In September 1996, a trench was dug in each field in two *Senna* alley cropping plots, perpendicular to the hedgerow, 15 cm away from the tree base, extending 2 m away from the trees, and 2 m deep. After leveling the profile wall, *Senna* root abundance was determined using a 10 by 10 cm grid by counting all living roots within each grid, after removing the top 1 mm of soil, following the method described by Akinnifesi et al. (1999). Dead roots were identified by their brittle structure and dark cortex. Roots > 5 mm, between 2 and 5 mm, and < 2 mm were counted separately.

After determining the root abundance, soil samples were taken from the profile wall with a 10 by 10 cm square auger (5 cm deep), 0.1, 0.5 and 1.5 m away from the tree base, from the following soil layers: 0-10, 10-20, 20-30, 50-60, 80-90, 110-120, and 140-150 cm. In Amoutchou, both root counting and soil sampling was restricted to 100 cm because of the high water table. In Glidji, soil was also destructively sampled at 190-200 cm. Separate soil samples were taken from the same layers for routine soil analysis (organic C (Amato, 1993); Kjeldahl total N; effective cation exchange capacity (IITA, 1982); base saturation; pH(H_20) (20 g dry soil in 50 ml H_2O); texture (IITA, 1982)). The diameter of the taproot was measured at 10 cm depth intervals up to a depth of 2 m, after taking the soils samples for root and soil characterization. Bulk densities were determined on the wall of a nearby soil profile, dug in 1995 to determine the soil type (Tossah et al., 1999).

The roots were removed from the soil collected with the 10 cm by 10 cm square augers by washing over a 0.5 mm sieve after submerging the samples overnight in a hexametaphosphate-Na-carbonate solution (20.94 g Na-hexametaphosphate L^{-1} and 4.45 g Na_2CO_3 L^{-1}) and stored in a 1% formaldehyde solution. Dead and live roots were separated as described above. The roots < 2 mm were spread evenly on a perspex sheet, scanned with Paintshop Program software, and the root length density (RLD) were measured with the Delta-T-Scan image analysis program (Webb et al., 1993). Preliminary investigations with a limited number of root samples showed a very close relationship between root lengths measured with the image analysis program and the original Tennant-method (Tennant, 1975).

Statistical methods

All root data were subjected to ANOVA with the MIXED procedure of the SAS system (Littell et al., 1996). Regression analysis between the various root characteristics was carried out with the REG procedure of the SAS system (SAS, 1985). Tap root diameters, root weight densities, and root length densities were log-transformed before ANOVA (Gomez and Gomez, 1984). Large (> 2mm) and small (< 2mm) root abundances, collected on the profile wall, were combined into 4 distances (0-50, 50-100, 100-150, and 150-200 cm away from the tree) and 6 depths (0-20, 20-40, 40-80, 80-120, 120-160, and 160-200 cm) for ANOVA analysis. Values for root abundance were log(n+1) transformed before statistical analysis (Gomez and Gomez, 1984). Two extremely large values for root length density measured on one of the two Glidji profiles (see below) were excluded from the statistical analysis. Means were estimated with the LSMEANS statement, while significantly different means were separated with the PDIFF test of the LSMEANS statement (Littell et al., 1996).

Results

Soil profile characteristics

The profile in Amoutchou contained mostly sand down to 1 m depth, while the profiles in Glidji and Sarakawa showed clay accumulation below 50 cm (Table 1). Consequently, the organic C and total N content and ECEC are higher in the subsoil in Glidji and Sarakawa than in Amoutchou. While the bulk density of the topsoil was similar in all sites, the bulk density of the layers below 40 cm was lower in Amoutchou than in both other sites (Table 2).

Abundance of roots

For all sites, the abundance of roots < 2 mm diameter in the 0-20 cm, 40-80 cm, and 80-120 cm layers was significantly ($P < 0.05$) higher between 0 and 0.5 m away from the hedgerow (21.4, 5.3, and

5.5 dm^{-2} in the 0-20 cm layer in Glidji, Amoutchou, and Sarakawa, respectively) than between 1.5 and 2 m away from the hedgerow (13.8, 3.1, and 3.7 dm^{-2} in the 0-20 cm layer in Glidji, Amoutchou, and Sarakawa, respectively) (Fig. 1). This was also true for the 20-40 cm layer in Amoutchou, for the 120-160 cm layer in Glidji and Sarakawa, and for the 160-200 cm layer in Sarakawa. Distance to hedgerow had no effect on the number of roots < 2 mm in the 20-40 cm layer in Glidji and Sarakawa (Fig. 1). In Glidji and Sarakawa, more shallow soil layers contained significantly ($P < 0.05$) more roots < 2 mm than deeper soil layers up to 120 cm depth at the 4 considered distances away from the tree base. Below 120 cm, differences between layers were not consistently significant. In Amoutchou, only the top 0-20 cm layer contained more ($P < 0.05$) roots < 2 mm than the deeper soil layers, while below 20 cm differences in root abundance were not consistently significant (Fig. 1).

In Glidji and Sarakawa, the abundance of roots > 2 mm in the 0-20 cm layer was significantly ($P < 0.05$) higher close to the hedgerow (0-0.5 m) (1.8 and 0.8 dm^{-2} in Glidji and Sarakawa, respectively) than furthest away from the hedgerow (1.5-2 m) (0.8 and 0.4 dm^{-2} in Glidji and Sarakawa, respectively) (Figs. 2a and 2c). Below 80 cm no differences in number of roots > 2 mm were observed for the considered lateral distances. In Amoutchou, all soil layers contained more ($P < 0.05$) roots > 2 mm closest to the hedgerow (0-0.5m) (1.1 dm^{-2} in the 0-20 cm layer) than furthest away from the hedgerow (1.5-2 m) (0.3 dm^{-2} in the 0-20 cm layer) except the 20-40 cm layer (Fig. 2b). Generally, in Glidji and Sarakawa, more shallow (0-80 cm) soil layers contained more ($P < 0.05$) roots > 2 mm, while in Amoutchou, only the 0-20 cm layer contained more ($P < 0.05$) large roots than the layers below 20 cm. Below 80 cm, no differences in large root abundance were observed between soil layers.

Root length densities and root weight densities

The root length density (RLD) of the 0-10 cm and 10-20 cm layers was significantly ($P < 0.05$) higher in Glidji (1.46 and 1.15 cm cm^{-3} in 0-10 and 10-20 cm layer, respectively) than in Amoutchou (0.50 and 0.22 cm cm^{-3} in 0-10 and 10-20 cm layer, respectively) (Fig. 3a). The 10-20 cm and 20-30 cm layers had a significantly ($P < 0.05$) higher RLD in Sarakawa than in Amoutchou. Differences in RLD between sites were not significant for layers below 30 cm (Fig. 3a). The 0-10 cm layer had a higher ($P = 0.08$) RLD under the tree than 1.5 m away from the tree (Fig. 3b). Deeper layers contained similar root length densities (RLD's) irrespective of the distance to the tree base (Fig. 3b). In Glidji, 2 soil cores (0-10 cm and 10-20 cm, both 0.5m away from the tree) in one of the profile pits contained very high RLD's (22.8 and 24.9 cm cm^{-3}, respectively), which were excluded from the statistical analysis, as mentioned previously.

The root weight density (RWD) of the 0-10 cm was similar in all sites (0.64, 0.44, and 0.56 mg cm^{-3} in Glidji, Amoutchou, and Sarakawa, respectively) (Fig. 4a). The 10-20 cm layer had a significantly ($P < 0.05$) higher RWD in Glidji than in Amoutchou. Differences in RWD between sites were not significant for layers below 20 cm (Fig. 4a). The 0-10 cm layer had a higher ($P = 0.09$) RWD under the tree than 1.5 m away from the tree (Fig. 4b). Deeper layers contained similar root length densities (RWD's) irrespective of the distance to the tree base (Fig. 4b).

Tap root diameter

At the soil surface, the taproot diameter was significantly ($P < 0.05$) larger in Glidji (215 mm) than in Amoutchou (91 mm) and in Sarakawa (77 mm) (Fig. 5). Between 10 and 50 cm, no significant differences in taproot diameter between sites were observed. Between 60 and 100 cm, the taproot diameter was significantly ($P < 0.05$) larger in Amoutchou than in Sarakawa (Fig. 5). For all sites, the taproot diameter decreased with soil depth, although differences between specific soil layers were not consistently significant (Fig. 5).

Correlations between selected root characteristics

For all sites, significant ($P < 0.001$) linear regressions were observed between RLD's, RWD's, and abundances of roots < 2 mm (Fig. 6). While the slopes of the regression lines relating RLD's with numbers of small roots were similar for all sites (Fig. 6a), the slope of the regression line relating RWD's with numbers of small roots was significantly higher for Amoutchou than for Glidji (Fig. 6b). The regression line relating RLD's with RWD's had a significantly higher slope for the Glidji data than for the data obtained on the other two sites (Fig. 6c).

In Amoutchou, the relative RLD, calculated based upon the regression lines presented in Fig. 6a, appeared to be lower than in Glidji or Sarakawa for the top 40 cm of soil, while the inverse was observed for the layers between 50 and 100 cm deep (Fig. 7).

Discussion

The soil profile characteristics influenced root abundance in the different soil layers. Although none of the soil layers in the top 1 m showed severe chemical (Table 1) or physical (Tables 1 and 2) restrictions to root growth, the soil layers below 50 cm contained a relatively higher RLD in Amoutchou than in the two other sites, most likely because of their more sandy texture (Table 1) and lower bulk density (Table 2). The taproot diameter in the layers below 50 cm was also larger in Amoutchou than in Sarakawa. The presence of local accumulations of roots observed in the Glidji topsoil and local increases in root abundances in the subsoil (Fig. 1) indicates that roots are not homogeneously distributed within a certain soil layer, but follow trails with minimal resistance to root growth, such as macropores or soil cracks. Rowe et al. (1999) reported a large variation in recoveries of subsoil ^{15}N-labeled ammonium sulphate by *Peltophorum dasyrrhachis* and attributed this to large heterogeneity in root distributions.

The larger values for root abundance in the topsoil in Glidji compared to Sarakawa was most likely caused by the more intense pruning regime, as the chemical and physical characteristics of the topsoil varied only little between the two sites (Tables 1 and 2). After all, in Glidji, the trees were pruned the first time already one year after planting and had been pruned 12 times prior to root quantification, while in Amoutchou and Sarakawa, the hedges grew for 4 years before their first pruning and had been pruned only 6 times before root quantification. Van Noordwijk and Purnomosidhi (1995) observed that a lower pruning height led to a larger number of superficial roots of smaller diameter on an Indonesian Ultisol. Schroth (1995) stated that shoot pruning of trees seemed to increase root branching in the topsoil and restrict tree roots to shallower soil depths compared with roots of unpruned trees. Although in Glidji also root length densities in the top 20 cm layer were much higher than in the two other sites, root weight densities were similar in all sites. This could be an indication that a more intensive pruning regime does not only lead to a larger number of superficial roots but also to roots with a smaller diameter. The necessity to prune the hedgerow trees in alley cropping systems during the cropping season results in a tree root system more comparable to the root system of an annual crop and, as such, reduces the potential of hedgerows to fulfill their hypothesized nutrient recovery potential. As regular pruning affects both the distribution of roots in the profile and their size, one could argue that screening of hedgerow trees for root competitiveness should be done on regularly-pruned trees and not on trees that are allowed to grow continuously.

The root safety-net zone is usually equated with that part of the soil profile from where trees recover substantial amounts of nutrients, not accessible to the associated food crop. Cadisch et al. (1997) developed an index for quantifying the nutrient recovery efficiency of the root safety-net - the safety-net efficiency - defined as the ratio [tree N uptake from the safety-net layer]:[tree N uptake from the safety-net layer + N leached beneath the safety-net layer]. A high safety-net efficiency requires a minimal RLD to a certain depth, a minimal level of activity of the roots present in the soil layers considered, and a minimal demand by the tree for the nutrient considered. Assuming that during the major part of the maize growing season few maize roots are found below 60 cm (Vanlauwe et al., 2001b), *Senna* root safety-nets could be identified in Glidji and Sarakawa with a thickness of at least 140 cm and minimal RLD's of 0.2 and 0.1 cm cm^{-3}, respectively. In Amoutchou, a *Senna* root safety net could be identified with a thickness reaching the upper boundary of the ground water table and a minimal RLD of 0.1 cm cm^{-3}. The safety-net was also observed to cover the complete alley from hedgerow to hedgerow, as the distance to hedgerow had only an impact on RLD's for the 0-10 cm soil layer, maximally 50 cm away from the tree base. The minimal RLD's needed for maximal nutrient uptake depend on the anion, but the safety-net hypothesis is usually linked to the recovery of nitrate-N as this nutrient is very mobile. Van Noordwijk (1989) estimated the minimal RLD to be 0.1 cm cm^{-3} for nitrate recovery and 1 cm cm^{-3} for K recovery. Although based on the observed RLD's the trees growing in all sites have the potential to recover a substantial amount of mineral N from the subsoil, some important processes and tree management aspects may hamper the optimal functioning of the root safety-net. Firstly, mineral N dissolved in water flowing preferentially through macropores may bypass any recovery mechanisms of mineral N by the trees. Vanlauwe et al. (2001a) observed substantial amounts of urea-derived N in the 120-150 cm soil layer already at 21 days after urea application and attributed this to preferential flow through macropores. Although tree roots may equally prefer to grow through macropores, it is doubtful whether water moving down macropores can be sufficiently fast absorbed by tree roots growing through these macropores. Secondly, the presence of roots in the subsoil does not necessarily mean that they are actively retrieving nutrients from the soil solution, although Schroth (1995) stated that the presence of roots from competitive crops such as maize may restrict the lateral spread of tree roots and force them into the subsoil. Vanlauwe et al. (2001a) also observed a larger recovery of ^{15}N-labeled ammonium sulphate by the maize than by the *Senna* hedgerow in an alley cropping trial. Evidently, during the dry season, trees will rely mostly on their subsoil roots for nutrient and water uptake. Thirdly, pruning of the tree canopy at the start of the food crop growing season strongly restricts the demand of the hedgerow for nutrients and water at a time where nutrient availability may be high due to the application of prunings and/or fertilizer and due to the presence of relatively large amounts of mineral N after the first rains caused by the so-called 'Birch' effect.

Although most of the soil layers in the Glidji profile contained a larger RLD than in the Sarakawa profile, especially in the top 20 cm, the average yearly pruning biomass productions was similar on both sites (9.2 and 9.7 t ha^{-1} in Glidji and Sarakawa, respectively – Tossah et al., 1999). The impact of a more dense root systems in Glidji is likely to be counteracted by the lower yearly precipitation, a lower top and subsoil fertility status (Table 1), and a higher competition with maize due to a relatively higher proliferation of tree roots in the same soil layers with maximal maize root densities. The very low yearly biomass production in Amoutchou (1.8 t ha^{-1} – Tossah et al., 1999) is likely caused by the very low soil fertility status of the complete profile and the temporarily high groundwater table which restricts nutrient uptake to the top 1 m during the rainy season.

The highly significant relationships between RLD's and RWD's and their relatively high R^2 values indicate that both root characteristics are closely related, irrespective of sampling depth or distance to hedgerow tree. For similar RWD's, *Senna* roots in Glidji had a significantly higher RLD, which confirms that they had a smaller diameter in Glidji than in the other two sites, as discussed earlier. Although the linear regressions between RLD's or RWD's and the number of small roots counted on a profile wall were highly significant, these regressions explained less of the variation than regressions between RLD's and RWD's. This may not be surprising as the ratio [RLD in a three-dimensional volume]:[number of roots visible on a two-dimensional plane] depends on the spatial arrangement of the tree roots and varies with sample position, sample depth, and sampling time (Van Noordwijk, 1987). As the relationships between RLD and small root abundance are quite similar for all sites, these could be used to estimate RLD's from root counting data on a profile wall, provided the relationship between the various root characteristics is known for the species of interest.

Conclusions

The sandy profile in Amoutchou resulted in a relatively higher proportion of RLD's in the subsoil and a larger tap root diameter compared to the Glidji and Sarakawa, of which the soil profile contained a clay accumulation horizon. The *Senna* roots contained more roots of a smaller diameter in Glidji than in Sarakawa, which was most likely the result of differences in tree management rather than soil profile characteristics.

In Glidji and Sarakawa, root safety-nets with a thickness of at least 140 cm and a minimal RLD of 0.2 and 0.1 cm cm^{-3}, respectively, were present. In Amoutchou, the thickness was limited due to the presence of a temporarily high groundwater table. However, the presence of tree roots at a certain depth does not prove that they are active. Moreover, several processes and tree management practices were identified which may lead to significant bypasses of the safety-net.

Close relationships were found between RLD's and RWD's indicating that RLD's could be estimated by a less tedious quantification of RWD's. Although the linear regressions between RLD's or RWD's and the number of small roots counted on a profile wall were highly significant, these regressions explained less of the variation than regressions between RLD's and RWD's.

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Table 1: Selected soil profile characteristics of the sites in Glidji, Amoutchou, and Sarakawa in Togo, West Africa.

Site/Soil depth	Organic C	Total N	ECEC[a]	BS[a]	pH (H_20)	Sand content	Silt content	Clay content
cm	%		$cmol_c$ kg^{-1}	%		%		
Glidji								
0- 10	0.31	0.030	2.0	100	5.28	89	4	6
10- 20	0.16	0.019	1.9	84	5.07	90	4	5
20- 30	0.18	0.023	2.8	75	5.03	83	3	13
50- 60	0.18	0.034	4.1	86	4.93	64	2	33
80- 90	0.16	0.031	3.8	95	5.13	61	3	35
110-120	0.12	0.029	4.1	88	4.58	58	3	38
140-150	0.10	0.025	3.6	92	4.78	60	3	37
190-200	0.11	0.025	4.4	86	4.82	55	3	42
Amoutchou[b]								
0- 10	0.29	0.022	2.9	100	5.33	86	9	4
10- 20	0.17	0.016	2.6	80	5.41	87	7	5
20- 30	0.14	0.014	3.4	81	5.48	86	8	5
50- 60	0.10	0.011	2.0	90	5.48	85	7	7
80- 90	0.08	0.011	3.6	81	5.24	78	8	13
Sarakawa								
0- 10	0.43	0.033	2.8	100	5.17	85	7	8
10- 20	0.30	0.025	2.8	84	5.18	82	9	9
20- 30	0.23	0.020	3.9	79	5.17	80	10	11
50- 60	0.33	0.039	4.8	68	4.49	47	7	47
80- 90	0.18	0.029	4.9	71	4.75	48	9	44
110-120	0.16	0.025	5.4	68	4.67	49	9	43
140-150	0.14	0.019	4.9	79	4.55	51	13	37
190-200	0.08	0.016	4.3	82	4.90	55	14	32

[a] 'ECEC': 'Effective Cation Exchange Capacity'; 'BS': 'Base Saturation'

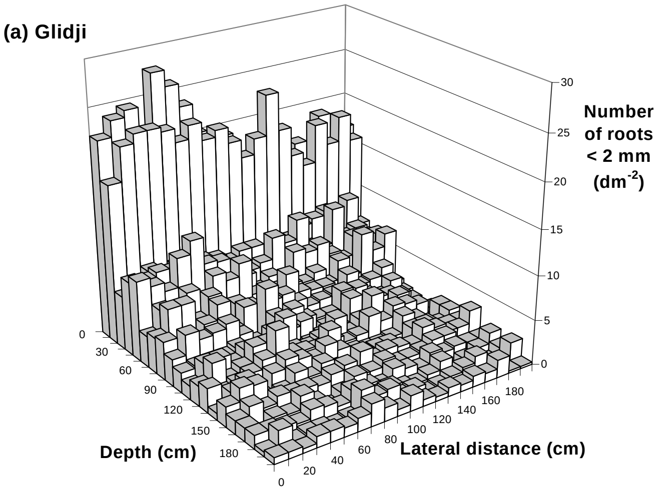
[b] Samples below 90 cm could not be taken because of water-logging during sampling

Table 2: Bulk density of the different soil layers at the sites in Glidji, Amoutchou, and Sarakawa in Togo, West Africa.

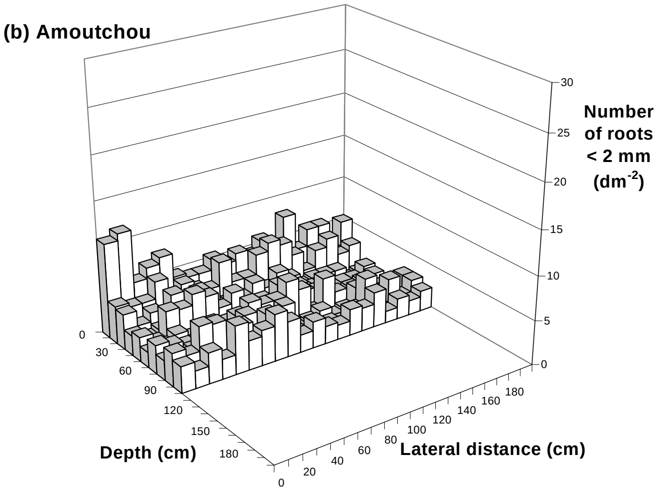
Site	Horizon (cm)	Bulk density (kg dm^{-3})
Glidji	Ap (0 - 15)	1.47
	E (15 - 40)	1.63
	Bt1 (40 - 95)	1.56
	Bt2 (95 - 120)	1.56
Amoutchou	Ah1 (0 - 20)	1.52
	Ah2 (20 - 35)	NA[a]
	E (35 - 50)	1.46
	Bw (50 - 85)	1.51
	Bg (85 - 100)	NA
Sarakawa	Ah1 (0 - 23)	1.50
	Ah2 (23 - 40)	1.50
	BA (40 - 50)	1.54
	Bt1 (50 - 80)	1.61
	Bt2 (80 - 112)	NA

[a] ‘NA’: ‘not available’

(a) Glidji



(b) Amoutchou



(c) Sarakawa

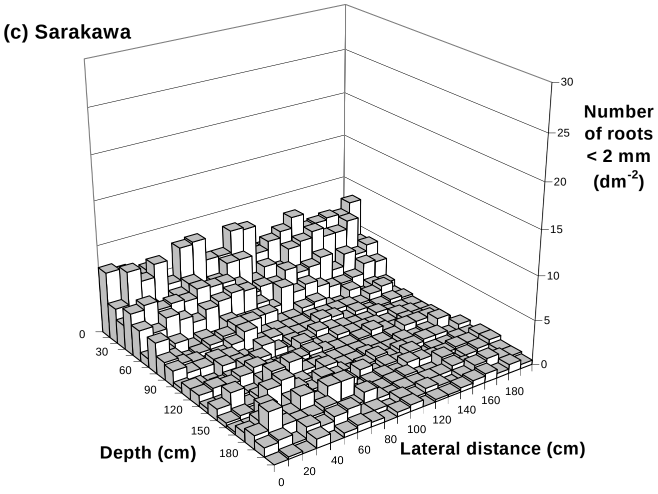
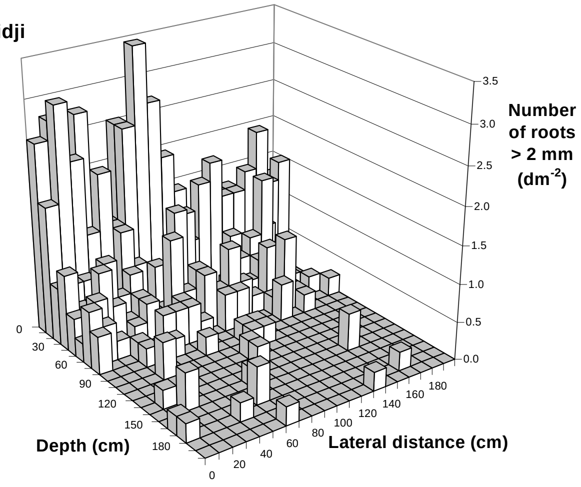
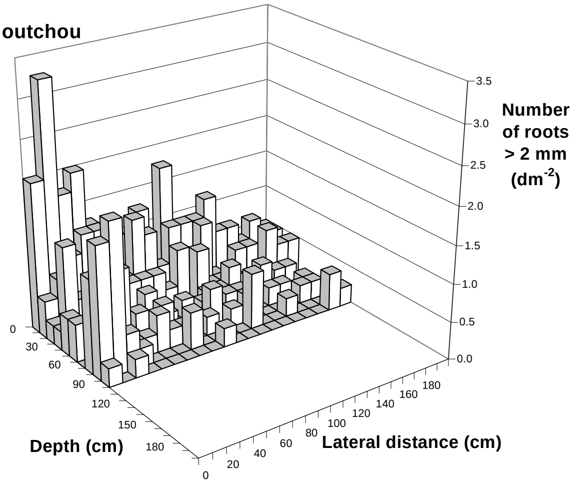


Fig. 1: Abundance of *Senna siamea* roots with a diameter < 2 mm in Glidji (a), Amoutchou (b), and Sarakawa (c) in Togo, West Africa, as influenced by soil depth and distance to the tree base. Values are averaged over the two halves of the two profile pits. Minimal and maximal standard errors of the differences between log(n+1)-transformed data are 0.044 and 0.062, 0.045 and 0.069, and 0.039 and 0.055, for Glidji, Amoutchou, and Sarakawa, respectively. Note that in Amoutchou no observations were taken below 100 cm.

(a) Glidji



(b) Amoutchou



(c) Sarakawa

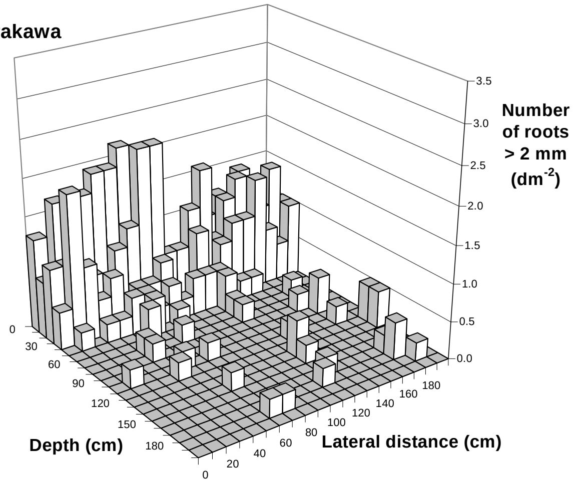


Fig. 2: Abundance of *Senna siamea* roots with a diameter > 2 mm in Glidji (a), Amoutchou (b), and Sarakawa (c) in Togo, West Africa, as influenced by soil depth and distance to the tree base. Values are averaged over the two halves of the two profile pits. Minimal and maximal standard errors of the differences between log(n+1)-transformed data are 0.020 and 0.028, 0.028 and 0.044, and 0.018 and 0.026, for Glidji, Amoutchou, and Sarakawa, respectively. Note that in Amoutchou no observations were taken below 100 cm.

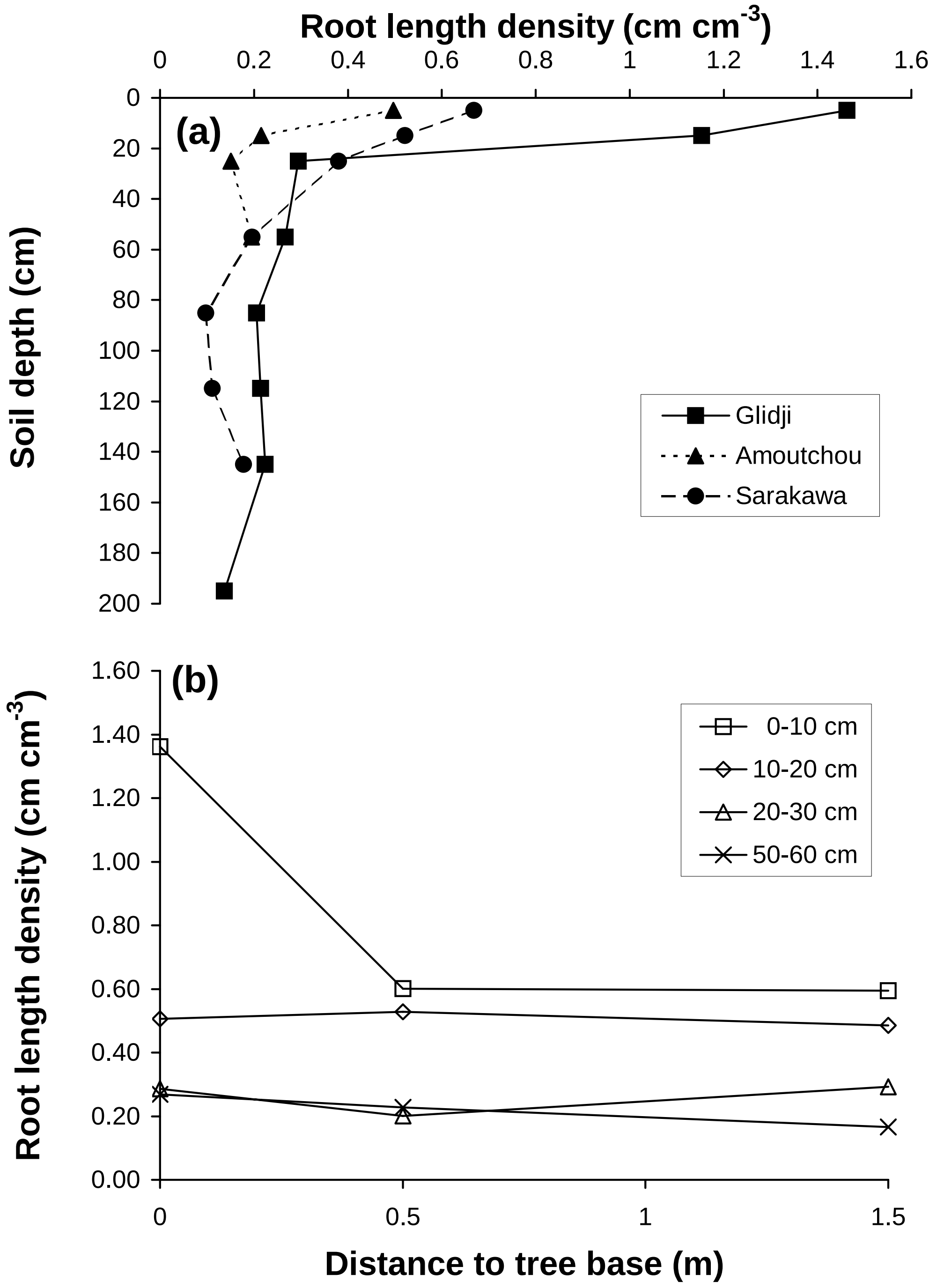


Fig. 3: *Senna siamea* root length density in Glidji, Amoutchou, and Sarakawa in Togo, West Africa, as influenced by soil depth (a) and distance to the tree base (b). The different sites were analyzed together. Minimal and maximal standard errors of the differences between log-transformed data are 0.17 and 0.25 for Fig. 3a and 0.15 and 0.23 for Fig. 3b. The interaction between site, soil depth, and distance to tree base was not significant. Note that in Amoutchou no observations were taken below 100 cm.

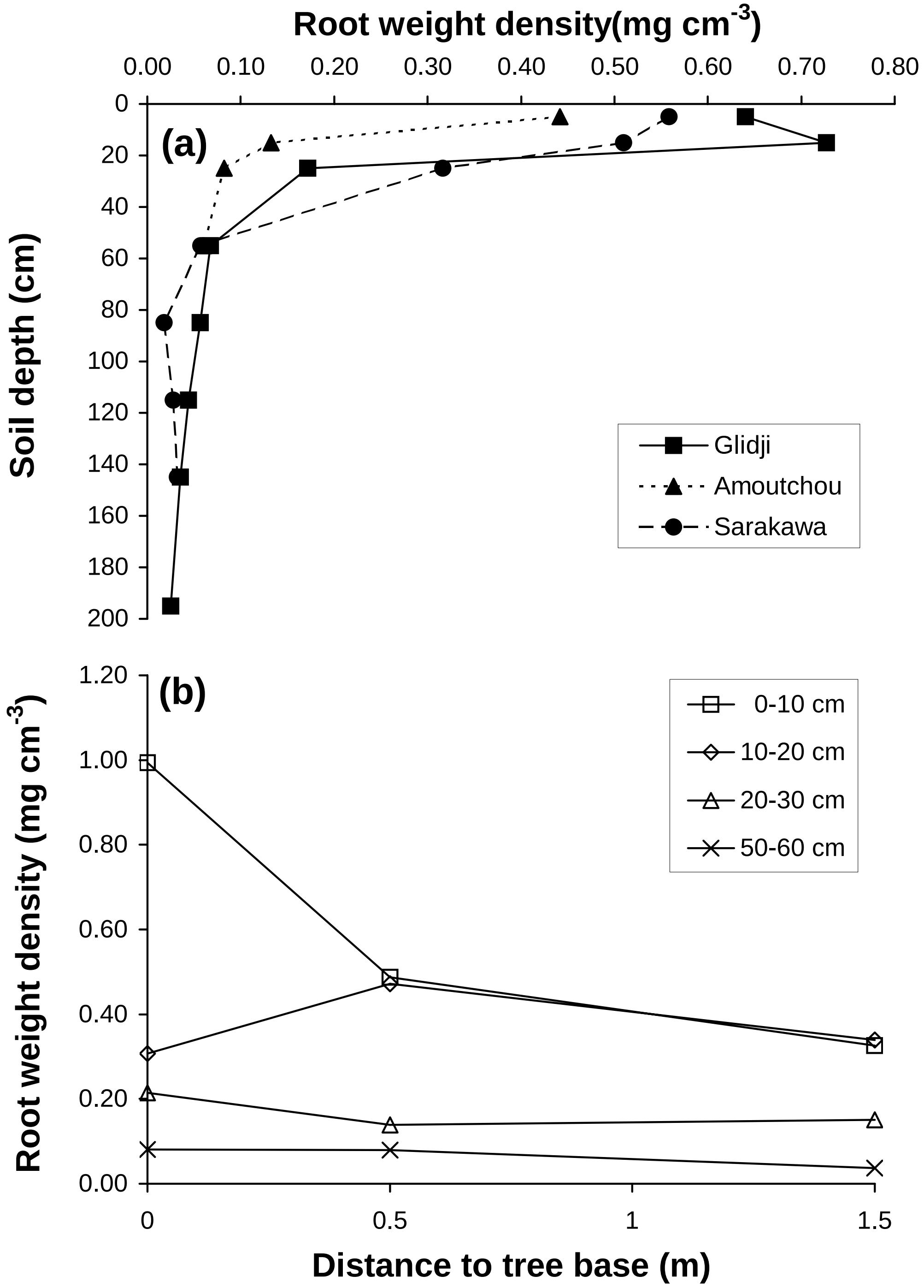


Fig. 4: *Senna siamea* root weight density in Glidji, Amoutchou, and Sarakawa in Togo, West Africa, as influenced by soil depth (a) and distance to the tree base (b). The different sites were analyzed together. Minimal and maximal standard errors of the differences between log-transformed data are 0.27 and 0.37 for Fig. 4a and 0.23 and 0.33 for Fig. 4b. The interaction between site, soil depth, and distance to tree base was not significant.

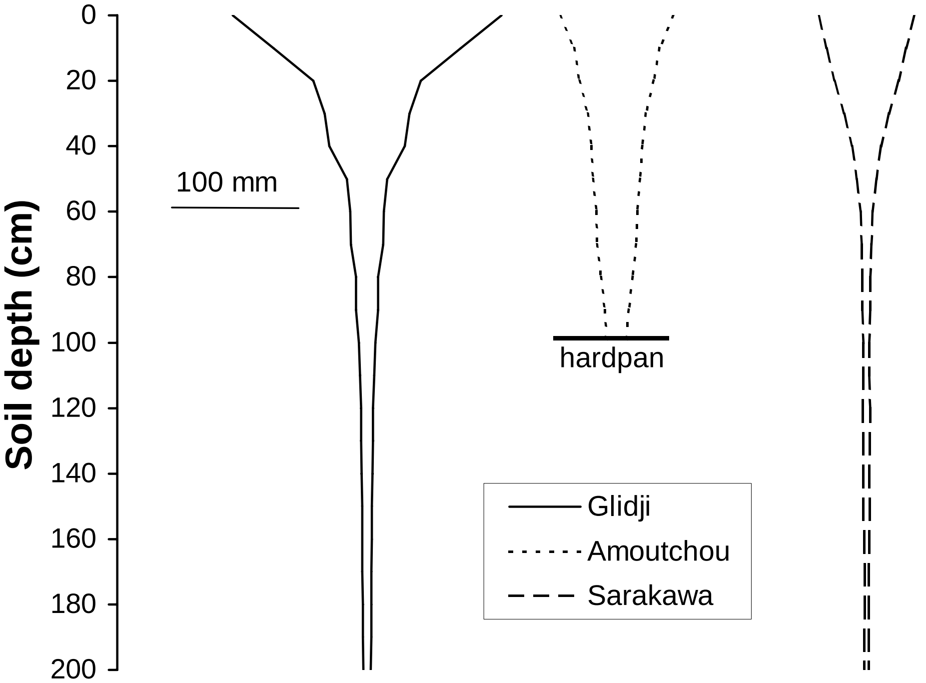


Fig. 5: Diameter of the *Senna siamea* taproot in Glidji, Amoutchou, and Sarakawa in Togo, West Africa. In Amoutchou, a hardpan prevented to measure the taproot diameter below 100 cm. The different sites were analyzed together. The standard error of the difference between log-transformed data to compare sites at similar depths is 0.22 and to compare depths at similar sites is 0.13.

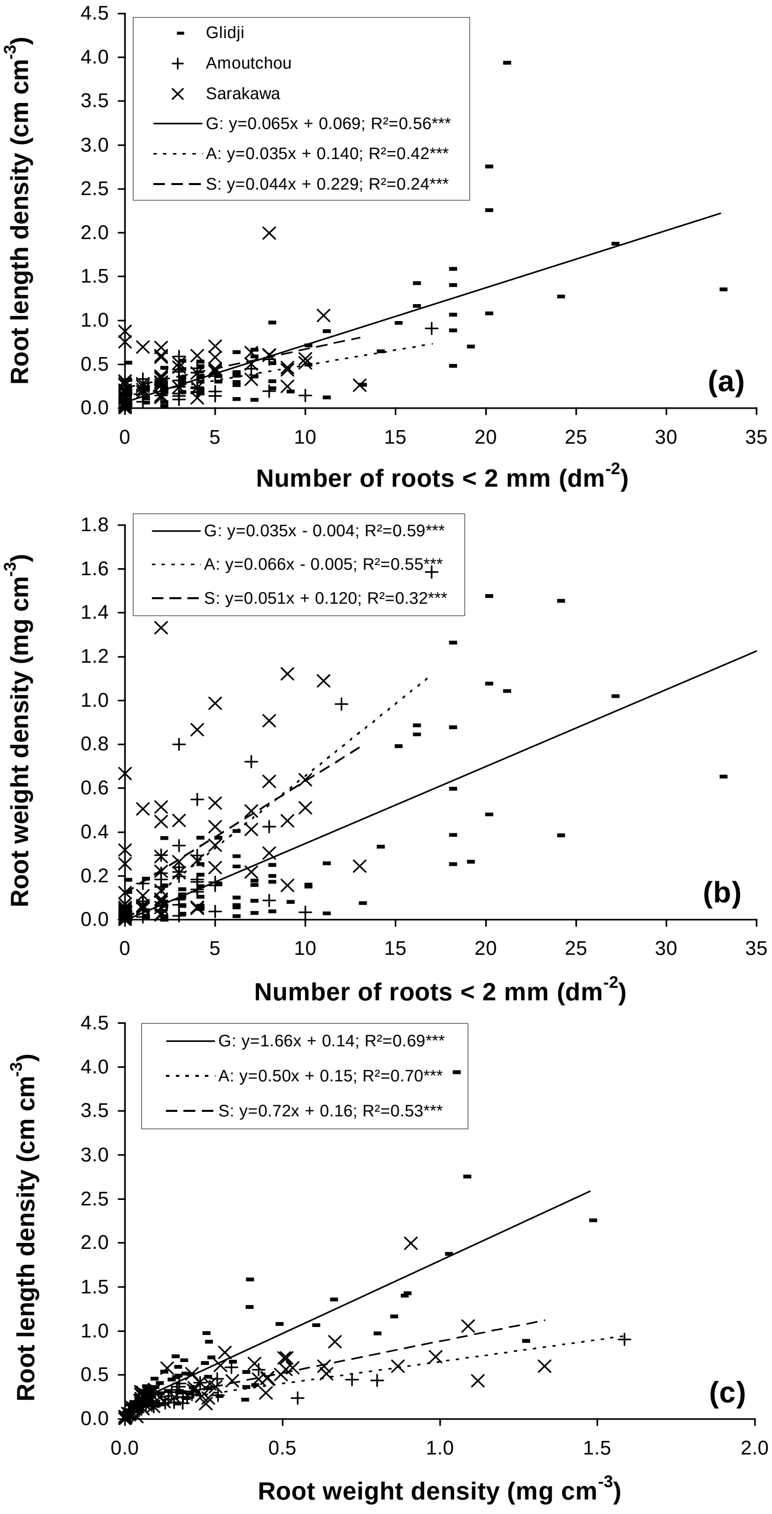


Fig. 6: Linear relationships between log-transformed root length densities and log(*n*+1)-transformed abundances of roots < 2 mm (a), between log-transformed root weight densities and log(*n*+1)-transformed abundances of roots < 2 mm (b), and between log-transformed root length densities and log-transformed root weight densities (c) for data obtained in Glidji, Amoutchou, and Sarakawa in Togo, West Africa.

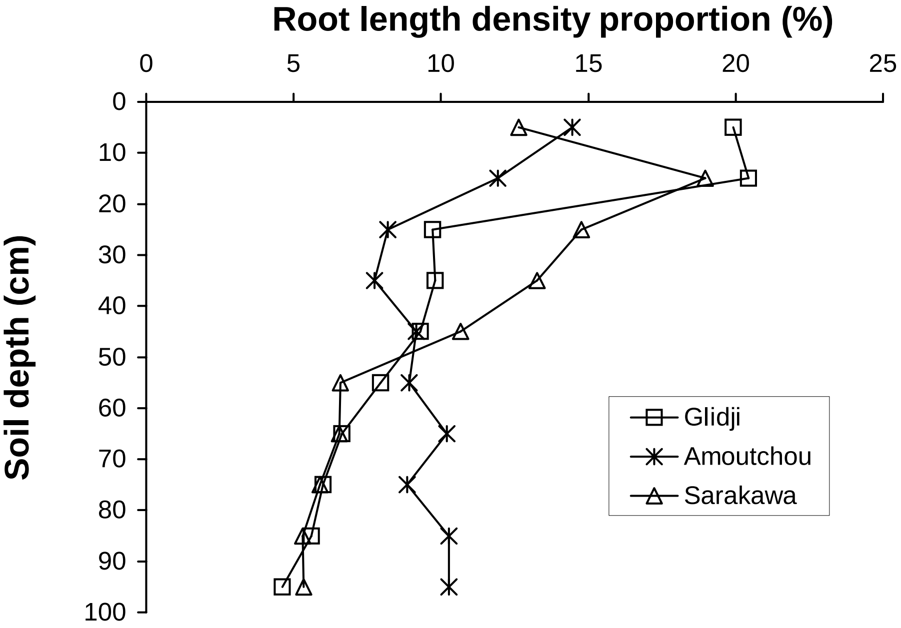


Fig. 7: Proportion of the total root length density of the top 1 m of soil in the various soil layers for the data obtained in Glidji, Amoutchou, and Sarakawa in Togo, West Africa. Root length densities were obtained after converting measured root abundances using the equations presented in Fig. 6a.

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Economics of Heap and Pit Storage of Cattle Manure for Maize Production in Zimbabwe

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Abstract

This study evaluates the profitability of using aerobic (heap) and anaerobic (pit) composted cattle manure for maize production. Pit storage of manure gave bigger yields of maize than heap storage in the year of application, and is much more profitable. Although the yields from heaped manure increase in the second and third years after manure application, over the three-year period pit storage is more advantageous.

Key words: profitability, manure storage, soil fertility, maize

Introduction

In many areas of Zimbabwe, farmers store manure for up to three months for use on field crops especially maize and finger millet. There are several manure storage techniques used, the predominant being heaping (Nzuma, Murwira and Mpepereki, 1998). Storing in pits (anaerobic composting) is a recent innovation that some farmers have tested (Nzuma and Murwira, 2000). This study assessed the profitability of pit and heap stored manure on maize production over a three-year period.

Materials and methods

The study was based on trials at Nhapi, Musegedi and Manyani in the Murewa Communal area from 1997/98 to 1999/2000. Manure which had been stored in pits and in heaps was applied at a rate equivalent to 100 $kgNha^{-1}$ in the first season only. No manure was applied to control plots. Ammonium nitrate fertiliser was applied at 100 $kgha^{-1}$ as top dressing yearly to all crops. Maize yield was measured over the three years. Grain price for the three seasons was obtained from the Grain Marketing Board and details of variable inputs were collected from Zimbabwe Farmers Union and the Department of Agricultural and Technical Extension Services.

Information on the labour involved in heap and pit storage was obtained from thirty households which owned cattle. This covered digging and heaping manure and transporting it to the field, the labour and cost of digging a pit, digging manure in the kraal, putting in a pit, covering it and taking manure out of a pit and carrying to the field. Gross margin analysis, Net Present Value (NPV) and Student T- distribution were used. The gross margin was the difference between gross income and total variable costs whilst NPV was calculated as the present worth of benefits less the present worth of costs (Gittinger, 1982).

The costs and benefits were discounted to reflect future values at 70%, this social discount needs to be high because the satisfaction of immediate needs is more urgent for most rural folk than the assurance of longer term benefits and also rainfall is unpredictable (Markandya and Pearce, 1991). Labour costs were deflated using annual inflation rates of respective years from 1998 to 2000 which were 37.2, 58.5 and 55.7 respectively (Reserve Bank of Zimbabwe, 2001). The corrected costs are included in the gross margin budget of these storage techniques during the year of manure application. Costs are in Z$ and a US$1 is equivalent to Z$55 as at August 2000.

Results and discussion

Of the 30 households interviewed, two families used pits only, four families used heaps only and 24 practised both. The mean number of days and costs of manure storage techniques are in table 1. Heaping required 1.0 to 9.0 days and pitting 2.5 to 11.0 days with means of 3.89 and 4.93 respectively. However, there was no significant difference between these means ($\bar{x} = 1.03$, t = 1.759 and p= 0.084).

Deflated costs of storage were used in the T- test. The cost of heaping varied from $18 to $231 and pitting ranged from $15 to $658 with means $87 and $133 respectively. Again, there was no significant difference between these costs ($\bar{x} = 46.00$,t = 1.628, p = 0.110).

In the year of manure application, pit stored manure had the largest gross margin ($2 184) and it was the only viable system (Table 1). Heaping (-$330) and the control (-$1363) both had negative gross margins which mean that they are unviable in this period. The adjusted yield from pit-stored manure was 5290 kgha^{-1} while heaping had 2600 kgha^{-1} (Figure 1).

In a laboratory analysis by Nzuma and Murwira (2000), pit stored manure had a higher N content (2.51% N) compared with 1.12% N for heaped manure at the time of manure application. This resulted in rapid nutrient release from pitted manure during the season hence higher yields. Therefore, manure quality affects profitability by dictating yield level. Heaping produces aerobically decomposed manure which has few nutrients available during the year of application. This would cause higher yield with pits in the first season.

Total costs, benefit streams and net incremental benefits are in Table 2. The profits realised from use of heaped manure increased over the three years while those from pit manure fell. Despite this, Mugwira and Mukurumbira (1986) found that with cattle manure yields are often higher with the second crop compared with the first. Total profit and yield of pit stored manure were greater than heaping because poor quality manure produced by heaping has a more pronounced residual effect than pitted manure. Costs of pit storage were higher ($9223) than for heap storage ($8809). The farmers' profits are not necessarily affected by the residual effect of cattle manure. Because of the residual effect, profits were expected to be greater for heaped manure than for pit stored but discounting of future benefits and costs offset this.

Conclusion

Pit storage of manure is more profitable for maize than heaping in the year of application and over three-years even though yearly profits and yields decreased. Heaping had a more pronounced residual effect in the second and third seasons.

Acknowledgements

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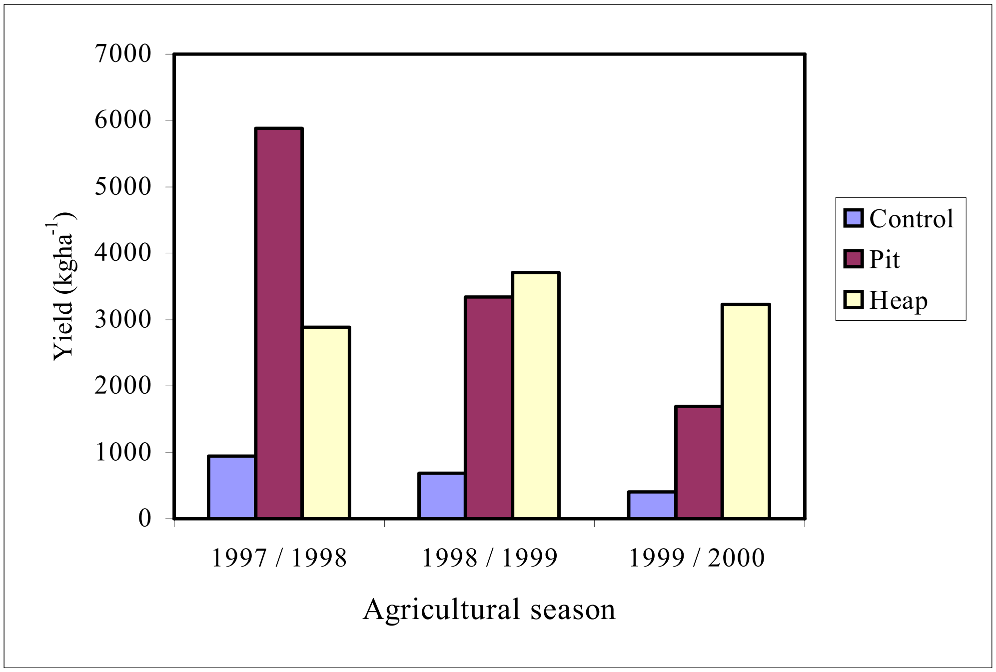

Figure 1: Average maize yield obtained from using heap and pit stored manure applied in the first season only

Table 1: Profitability of manure options during first year (1997-1998) (Z$)

Storage System	Total Benefits	Total Costs	Gross Margin	Rate of return ($/$100 Variable Cost)
Pit	6 350	4 164	2 187	52.5
Heap	3 121	3 451	-330	-9.57
Control	1 015	2 378	-1 362	-57.3

Table 2: Seasonal costs, benefits and profits during three seasons

Season	Cost of pitting (Z$)	Benefits of pitting (Z$)	Net incremental benefit (pit) (Z$)	Cost of heaping (Z$)	Benefits of heaping (Z$)	Net incremental benefit - heap (Z$)
1997-1998	4 166	6 350	2 185	3 451	3 121	-330
1998-1999	2 936	4244	1 308	3 038	4 714	1 676
1999-2000	2 134	2 210	76	2 319	4 225	1 906

Draft Paper

Pathways Towards Integration of Legumes into the Farming Systems of East African Highlands.

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Abstract

Food legumes remained to be important components of various farming systems of Eastern Africa, while the attempt to integrate fodder legumes and legume cover crops (LCCs) since 1930s became unsuccessful. Farmers remained reluctant to integrate fodder legumes and LCCs, despite recognising their benefits as soil fertility restorers and high value feeds, mainly due to community/farmer specific socio-economic factors. Farmers' participatory research was conducted in Ethiopian Highlands to understand the processes of integration of legumes of different use into mixed subsistent farming systems. Areka had an altitude of 1990 masl, and rainfall amount of 1300mm, which is characterised by poor access to resources, intensive cropping, land shortage and soil degradation. Firstly participatory evaluation was conducted on the agronomic performance and adaptability of eight legumes during the main and small growing seasons of 2000 and 2001. The treatments were Vetch, Stylosanthus, Crotalaria, Mucuna, Canavalia, Tephrosia, Field pea and Common bean. Following the agronomic evaluation, the perception of farmers to legumes of different use, the socio-economic factors dictating choices and adoption, and potential niches for legume integration into the cropping systems were considered. Dry matter production among legumes was significant regardless of the length of growing period. For short term fallows, 3 months or less, Crotalaria gave significantly higher biomass yield (4.2 t ha $^{-1}$) followed by Vetch and Mucuna (2 t ha^{-1}), while for medium-term fallow, 6 months, Tephrosia was best performing species (13.5 t ha^{-1}) followed by Crotalaria (8.5 t ha^{-1}). The selection criterion of farmers was far beyond biomass production. Farmers identified firm root system, early soil cover, biomass yield, decomposition rate, soil moisture conservation, drought resistance and feed value as important criteria. There was significant difference in soil moisture conservation among LCCs, and decreased in order of Mucuna (22.8%), Vetch (20.8 %), Stylosanthus (20.2 %), bare soil (17.1 %), Crotalaria (14 %), Canavalia (14 %) and Tephrosia (11.9 %), respectively. The overall sum of farmers' criteria showed that Mucuna followed by Crotalaria could be the most fitting species, but farmers finally decided for Vetch, the low yielder, due to its fast growth and high feed value because of their priority to livestock feed than soil fertility. The final decision of farmers for integrating a non-food legume into their temporal & spatial niches of the system depended on land productivity, farm size, land ownership, access to market and need for livestock feed. The potential adopters of LCCs and forage legumes were less than 7%, while 91% of the farmers integrated the new cultivars of the food legumes. After characterising the farming systems of other benchmark sites, those indicators were used for development of decision guides to be used for integration of legumes into multiple cropping systems of East African Highlands.

1. Introduction

Food legumes remained to be important components of various farming systems of Eastern Africa as they are the sole protein sources for animals and humans. Besides restoring soil fertility, legumes are grown in rotation with cereals mainly because they accompany the stable cereals in the local dishes. On the other hand, the attempt to integrate fodder legumes and legume cover crops (LCCs) since 1930s became unsuccessful. Farmers remained reluctant to integrate fodder legumes and LCCs, despite recognising their benefits as soil fertility restorers and high value feeds, mainly due to community/farmer specific socio-economic factors. However, as farmers export both grain and stover from the field, the amount of legume residue left to the soil is too small to have a profound effect on restoration of soil fertility.

Degradation of arable lands became the major constraint of production the Ethiopian Highlands, due mainly to nutrient loss resulting from soil erosion, lack of soil fertility restoring resources, and unbalanced nutrient mining (Amede et al., 2001). However, most farmers in the region have very low financial resources to combat nutrient depletion, and hence research should be directed to seek affordable and least risky, but profitable amendments necessary to keep nutrient balance neutral (Versteeg et al., 1998). In 1999 and 2000, researchers of the African Highlands Initiative (AHI) conducted farmers participatory research on maize varieties on a degraded arable land in Southern Ethiopia, Areka, by applying inorganic fertilisers. Although the soil is an Eutric Nitisol deficit in nitrogen phosphorus (Waigel, 1986), high level application of inorganic N and P did not improve maize yield. Lack of response to inorganic fertilisers because of low soil organic matter content was also reported elsewhere (Swift and Woomer, 1993). Organic inputs could increase the total amount of nutrients added, and also influence availability of nutrients (Palm et al., 1997). However, more than 50% of the organic resource available in the region is maize stalk, of which 80% is used as a fuel wood (Amede et al., 2001). The strong competition for crop residues between livestock feed, soil fertility and fuel wood in the area limits the use of organic ferilizers unless a suitable strategy that builds the organic resource capital is designed. Fallowing for restoration of soil fertility is no more practised in the region due to extreme land shortage.

One strategy could be systematic integration of legume cover crops into the farming system. Organic inputs from legumes could increase crop yield through improved nutrient supply/availability and/or improved soil-water holding capacity. Moreover, legumes offer other benefits such as providing cover to reduce soil erosion, maintenance & improvement of soil physical properties, increasing soil organic matter, cation exchange capacity, microbial activity and reduction of soil temperature (Tarwali et al., 1987; Abayomi et al., 2001) and weed suppression (Versteeg et al., 1998). There are several studies in Africa that showed positive effects of Legume Cover Crops (LCCs) on subsequent crops (Abayomi et al., 2001; Fishler & Wortmann, 1999; Gachene et al., 1999; Wortmann et al., 1994). Studies in Uganda with Crotalaria (Wortmann, et al., 1994; Fishler and Wortmann, 1999), and in Benin with Mucuna (Versteeg et al., 1998) showed that maize grown following LCCs produced significantly higher yield than those without green manure. The positive effect was due to high N& P benefits and nutrient pumping ability of legumes from deeper horizons. However, the success rate in achieving effective adoption of LCCs and forage legumes in Sub-saharan Africa has been low (Thomas and Sumberg, 1995) since farmers prefer food legumes over forage or/legume cover crops in that the opportunity cost is so high to allocate part of the resources of food legumes to LCC. Therefore, there is a need to develop an effective guideline that targets different legume types in different niches of different agro-ecologies and socio-economic strata.

The objective of this paper was, therefore a) to analyse the distribution of legumes in the perennial- based (Enset-based) systems, b) test the performance of legumes under short term and medium term periods, c) identify the potential causes of non-adoption of LCC, and d) develop preliminary decision guides that could be used to integrate LCC in small scale farms with various socio-economic settings.

2. Materials and Methods

2.1. Location, Climate and Soil

The research was conducted at the Gununo site (Areka), Southern Ethiopian Highlands. It is situated on 37° 39' E and 6° 51' N, at an altitude range between 1880 and 1960 m.a.s.l The topography of the area is characterised by undulating slopes divided by v-shaped valleys of seasonal and intermittent streams, surrounded by steep slopes.

The mean annual rainfall and temperature is about 1350 mm and 19.5 °C, respectively, with relatively low variability, in terms of amount of precepitation, over the years. The rainfall is unimodal with extended growing periods from March to the end of October, with short dry spell in June. The highest rainfall is experienced during the months of July and August and caused soil loss of 27 to 48 t ha^{-1} (SCRP, 1996). The dominant soils in the study area are Eutric Nitisols, very deep (>130 m), acidic in nature. These soils originated from kaolinitic minerals which are inherently low in nitrogen and phosphorus (Waigel, 1986). Soil fertility gradient decreases from homestead to the outfield due to management effects.

2.2. Participatory evaluation of LCCs

The research site has relatively very high human population density with an average land holding of 0.5 ha household$^{-1.}$ Using LCCs for soil fertility purposes is not a common practise in the area. LCCs were introduced into the system in 2000 following a farmers field school (FFS) approach so as to allow farmers to learn and appreciate various legumes uncommon to the area. The farmers research group (FRG) was mainly composed of mainly men, despite the repeated temptation of researchers to include women. The legumes were planted in two planting dates. The on-farm experiments, used simultaneously for FFS and also for evaluation of biomass productivity and after effect of legumes on the following maize crop, were planted on April 25, 2000 and July 1, 2000 and harvested on October 6, 2000 and January 6, 2001, respectively, using recommended seed rates. The interest of the farmers was to evaluate the effect of planting dates and length of fallow period on biomass productivity of respected species, and to identify the best fitting legumes for a short-term fallow (three months) or medium term (six months) fallow. Long-term fallow became impractical due to land scarcity. Thirty interested farmers, who were organised under one farmers research group (FRG), have studied six different species namely, Stylosanthus (*Stylosanthus guianensis*), Crotalaria (*Crotalaria ochroleuca*), Mucuna (*Mucuna pruriens*), Tephrosia (*Tephrosia vogelii*), Vetch (*Vicia dasycarpa*) and Canavalia (*Canavalia ensiformis*). All LCC were exotic species to the system except Stylosanthus. We also included two food legumes, namely common bean (*Phaseolus vulgaris*) and Pea (*Pisum sativum*), in the study that were existing in the farming system. The FRG studied and monitored growth and biomass productivity in short and long seasons of 2000. The researchers were involved mainly in facilitation of continual visits and stimulation of discussions among farmers. Farmers and researchers were recording their own data independently. After intensive discussion, the FRG identified six major criteria to propose one or the other legume to be integrated into the system. Since farmers considered soil water conservation as one important criterion for selecting LCCs, soil water content was determined under the canopy of each species at top 25-cm depth gravimetrically. Sampling was done in relatively dry weeks of November 2000, five months after planting. We considered four samples per plot, weighed immediately after sampling, oven dried the samples with 120 ^{o}C for a week before taking dry weight. Legume ground cover was determined using the beaded string method, knotted at 10-cm interval and laid across the diagonals of each plot, 12 weeks after planting. A supplemantary replicated on-farm experiment (a plot size of 12 m^2, three replications) was conductedto evaluate biomass production of LCCs under partially controlled replicated experiment to verify earlier obtained results. It was also meant to identify the most promising species for short term fallow, as farmers were reluctant to allocate land for LCCs beyond three months. The species were planted on October 12, 2001 and harvested on January 10, 2002. The legumes received phosphorus at a rate of 30 kg/ha P_2O_5 at planting. After four months of vegetative growth, the green biomass of the legumes was weighed and incorporated directly to the soil. Maize (var A511) was planted about one month after incorporation on all plots. Three additional nitrogen treatments were included namely, 0 N, 30 N and 60 N per hectare to draw a nitrogen equivalent curve.

In August 2002, after farmers monitored the introduced legumes, 26 farmers from four villages selected species of their choice LCC and tested them in their farms together with a food legume, Pea. During the growing seasons of 2000 and 2001, we monitored which farmer selected what, how did they manage the LCCs in comparison to the food legume and for what purpose the legumes were used. Biomass production of the various legumes under farmers' management was also recorded. Besides structured questionnaire and formal survey (Pretty et al., 1995), an informal repeated on-field discussion using transect walks were used to identify the socio-economic factors that dictated farmers to choose one or the other option and to prioritise the most important criteria of decision making using pair wise analysis matrix. More over, farmers invited non-participating neighbouring farmers for discussion; hence the decision made is expected to represent the community.

The tested species were those most favoured by farmers for further integration namely Crotalaria (*Crotalaria ochroleuca*), Mucuna (*Mucuna pruriens*), Tephrosia (*Tephrosia vogelii*), Vetch (*Vicia dasycarpa*) and Canavalia (*Canavalia ensiformis*) replicated three times arranged in a randomised block design. The plot size was 12 m2, with one-meter gangway between treatments. The field was weed free through out the season by hand weeding. In all cases, phosphorus was applied at a rate of 13-Kg ha-1 to facilitate growth and productivity. Data on biomass production of the species was analysed by ANOVA using statistical packages (Jandel Scientific, 1998).

Using the qualitative and quantitative data obtained from the site, and by considering the hierarchy of indicators identified by farmers, we developed draft decision guides on the integration of legumes into the farming systems of the Ethiopian Highlands.

3. Results and Discussion

3.1. Land use and Soil fertility management

The major land use systems in the community include homestead farms, which are characterised by soils with high organic matter content due to continuos application of organic residue. These soils are dark brown to black in colour mainly due to high organic matter content. This part of the farm was used to grow the most important crops such as enset (*Enset ventricosum*), coffee, vegetables, planting materials for sweet potato and raise tree seedlings are grown. In the system only about 3% of the homestead are occupied by legumes intercropped under the enset/ coffee plants (data not presented). Farmers are not applying inorganic fertiliser in this part of the farm. The homestead field is followed by the main field, which is characterised by red soils. Red soils are considered by the farmers as less fertile due to limited application of organic inputs, hence require application of inorganic fertiliser to get a reasonable amount of yield. In this part of the farm, farmers grow maize in association with taro, beans and sweet potato. This is also where legumes are growing most. The outfield is the most depleted and commonly allocated for growing maize or potato using inorganic fertlizers. This plot does not receive any organic manure, legumes are rarely planted and the crop residue is even exported for different purposes. Farmers do not practice intercropping in this part of the land. Although legumes are major components of the system, the primary objective of the farmers is production of food grains as sources of protein followed by feed production as a secondary product, but not soil fertility. That is also partly the reason why the amount of land allocated for legumes decreases with distance from the homestead (decreasing soil fertility).

3.2. Participatory Evaluation of Legume Cover Crops and their after effects

The rainfall distribution was favorable and there was no extended dry spell within the growing season of 2000 and 2001. For the medium-term fallow, Tephrosia produced the highest dry matter biomass yield, 13.5 t ha^{-1} followed by Crotalaria, 9 t ha^{-1}. In the three months growing period, the herbaceous legumes varied in biomass productivity significantly. Crotalaria and vetch were fast growing and also early maturing than the others. On the other hand, tephrosia was growing relatively slow at the initial stage of growth, which is reflected in the biomass accumulation. Accordingly, the biomass yield of crotalaria was significantly higher than the other legumes, while the biomass of tephrosia was much lower than all the others (Fig.1). A similar experimental result was also obtained in the previous seasons on onfarm trials. Most of the biomass accumulation in Tephrosia was observed four months after planting. For the short-term fallow, Crotalaria was the best performing species followed by Mucuna and Vetch. On individual farmer's field, Crotalaria was the best performing species regardless of soil fertility. Similar results were reported from Uganda (Wortmann et al., 1994). On the other hand, vetch and mucuna were performing best in fertile corners of the farms. This did not agree with the findings of Versteeg et al., (1998), which indicated that mucuna performed better than other green manures (including crotalaria) to recover completely degraded soils. When those species were planted in the driest part of the season, crotalaria and mucuna performed best and produced up to 2.9 t ha^{-1} dry matter with in three months of time (data not presented). Besides dry matter yield, we measured soil water content under the canopies of LCCs. The data showed that, the highest soil water content was obtained from mucuna and stylosanthus, which could be due to the self-mulching (Table 2). The ground cover (%) was the highest for Mucuna (100 %), and the lowest for vetch (60%). A similar result was obtained for mucuna in western Nigeria (Abayomi et al., 2001). Higher soil water content under mucuna &, stylosanthus implies that these species could improve soil water availability through reduction of evaporative loss if grown in combination with food crops.

The result showed that maize grown after legumes produced significantly higher grain yield than the check (maize grown with out nitrogen fertiliser) and gave a maize yield at least equivalent to 30 kg of N/ha regardless of the legume species (Fig 1). The yield obtained from the plots of vetch, canavalia and mucuna was almost similar, while the yield obtained from crotalaria and tephrosia plots was significantly lower than that of the other species. Although the biomass of crotalaria incorporated to the soil was much higher than the others, the effect was not evident on maize yield. This could be explained by the fact that crotalaria had very high lignin content than the others at the time of harvesting and incorporation, which possibly affected the processes of decomposition and nutrient release.

By considering the type of produce the farmers grow in the neighbouring field of equal size, which was sweet potato, and calcultating the costs and benefits of the LCCs and neighboring field, we found out that the opportunity cost of growing LCCs was much higher than anticipated. The maize yield gain obtained after growing LCCs in a short season should be more than two folds for the farmer to consider growing LCCs as potentially profitable interventions.

Fig. 1. Biomass production of various legume cover crops grown in Nitisols for three or six months of growing period under highland conditions (n=3).

Farmers evaluated the performance of LCCs in the fields individually or in groups through repeated visits. The selection criteria of farmers were beyond biomass production (Table 1). After intensive discussion among them selves, the FRG agreed on seven types of biophysical criteria to be considered for selection of LCCs (Table 1). However, the criteria of choice had different weights for farmers of different socio-economic category. None of the farmers mentioned labour demand as an important criterion. They considered firm root system (based on the strength of the plant during uprooting), rate of decomposition (the strength of the stalk and or the leaf to be broken), moisture conservation (moistness of the soil under the canopy of each species), drought resistance (wilting or non-wilting trends of the leaf during warm days), feed value (livestock preference), biomass production (the combination of early aggressive growth and dry matter production) and early soil cover. For resource poor farmers (who commonly did not own animal or own few) food legumes were the best choices. For farmers who own sloppy lands with erosion problems mucuna and canavalia were considered to be the best: Mucuna for its mulching behaviour and canavalia for its firm root system that reduced the risk of rill erosion. Farmers with exhausted land selected crotalaria, as all the other legumes were not growing well in the degraded corners of their farms. On the other hand, farmers with livestock selected legumes with feed value and fast growth (Vetch and Stylosanths). In general, Vetch was the most favoured legume despite low dry matter production, as it produced a considerable amount of dry matter within a short period of time to be used for livestock feed. It was also easy to incorporate into the soil and found it to be easily decomposable. The over all sum of farmers' ranking, however, showed that mucuna followed by crotalaria are the best candidates for the current farming system of Areka. Since Mucuna is aggressive in competition when grown in combination with other crops (Versteeg et al., 1998) it could be used to increase soil fertility in well established Enset/Coffee fields, while Crotalaria and Canavaia could be used to ameliorate exhausted outfields. Canavalia is found to be best fitting as an intercrop under maize as it has deep root system and did not hang on the stocks of the companion crop (personal observation). The herbaceous LCCs are reported to be of high quality organic resources (Gachene, et al., 1999) to be used as organic fertilisers directly to improve the grain yield of subsequent crops (Caamal-Meldonado et al., 2001; Abayomi et al., 2001).

Table 1. Farmers' criteria of selection of legume cover crops. According to farmers' ranking 6 was the highest and 1 the lowest (n=25).

Species	Firm roots	Early soil cover	Bio-mass	Rate of decom-postion	Moisture conser-vation	Drought resist-ance	Feed value	Sum Total
Crotalaria	2	6	6	6	2	2	2	26
Vetch	1	5	5	4	1	1	6	23
Mucuna	6	4	3	3	6	6	4	32
Canavalia	5	3	4	1	4	5	2	24
Tephrosia	3	2	2	2	5	3	2	19
Stylosanthus	4	1	1	5	3	4	5	23

3.3. Farmers' Management of LCCs

After thorough monitoring about the productivity and growth behavior of LCCs in the experimental plots, 26 farmers have tested various LCCs in their own farm. They tried mainly Canavalia, Crotalaria, Mucuna, Stylosanthus and Vetch. We documented that farmers selected the most degraded corners of the farm for growing LCCs and the fertile corners of their land for growing Pea (Table 2). About 50% of the trial farmers allocated depleted lands (degraded and abandoned) for the LCC. Further discussion with farmers revealed that they took this type of decision partly due to fear of risk, and partly not to occupy land that could be used for growing food crops.

Table 2. Spatial niches identified by farmers for growing Legume Cover Crops or Food legumes (Pea) in the growing seasons of 2000. Data shows number of involved farmers (%) grew legumes at different spatial niches (n=26).

Crop type	Sole in fertile soil	Sole in degraded soil	Relay under Maize	Steepy land	Border strips	abandoned land
Legume Cover Crops	0	28.6	7.1	14.3	21.43	21.42
Pea	64.29	0	35.7	0	0	0

From the total respondents, 86.6% of the farmers knew about the role of green manures as soil fertility restorers (Fig. 2). However only 63% of them tested LCCs and of those who tested the green manures only 21 % responded LCCs were effective in improving the fertility status of the soil. About 79% believed that LCCs may not feet into their system mainly because they did not emerge well, or showed poor performance under depleted soils or are competing with food legumes for resources (labour, water and land) (Fig. 2). This was manifested by the fact that almost all of the farmers planted LCCs on the degraded corners of their farm (Table 2), which in turn caused low biomass production and generally poor performance of LCCs (data not presented).

Fig 2. Schemes used for identification of factors of adoption or non-adoption of legume cover crops in multiple cropping systems of Areka.

3.3. Socio-economic Factors Dictating Integration of Legumes

Results from informal interviews followed by structured questioner showed that there are 21 different factors that affect the integration of legumes of different purposes. When farmers were asked to prioritise the most important factors that affect adoption and integration of legumes, farmers mentioned a) farm size b) suitability of the species for intecropping with food legumes c) productivity of their land d) suitability for livestock feed e) marketability of the product f) toxicity of the pod to children and animals g) who manages the farm (self or share cropping) h) length of time needed to grow the species and I) risk associated with growing LCCs in terms of introduction of pests and diseases.

Earlier works suggested that farm size and land ownership effect integration of LCCs into small holder farms (Wortmann & Kirungu, 1999). After comparing those factors in a pair wise analysis, four major indicators of different hierarchy were identified (data not presented).

1) Degree of land productivity: Farmers in Gununo associated land productivity mainly with the fertility status of the soil and distance of the plot from the homestead. The homestead field is commonly fertile due to continual supply of organic resources. Farmers did not apply inorganic fertiliser in this part of the farm. They remained reluctant to allocate a portion of this land to grow LCCs for biomass transfer or otherwise, but they grow food legumes, mainly beans, as intercrops in the coffee and enset fields. The potential niche that farmers were willing to allocate for LCCs is the most out field.
2) Farm size: Despite very high interest of farmers to get alternative sources to inorganic fertilisers the probability that farmers may allocate land for growing LCCs depended on the size of their land holdings. For Areka conditions, a farm size of 0.75 ha is considered as large. Farmers with very small land holdings did not grow legumes as sole crops, but integrate as intercrops or relay crops. Therefore, the potential niches for LCCs are partly occupied unless their farm is highly depleted.
3) Ownership of the farm: Whether a legume (mainly LCCs) could be grown by farmers or not depended on the authority of the person to decide on the existing land resources, which is linked to land ownership. Those farmers who did not have enough farm inputs (seed, fertilizer, labour and/or oxen) are obliged to give their land for share cropping. In this type of arrangement, the probability of growing LCCs on that farm is minimal. Instead, farmers who contracted the land preferred to grow high yielding cereals (maize & wheat) or root crops (sweet potato). As share cropping is an exhaustive profit-making arrangement, the chance of growing LCCs in such type of contracts was almost nil. Without ownership or security of tenure, farmers are unlikely to invest in new soil fertility amendment technology (Thomas and Sumberg, 1995)
4) Livestock feed: In mixed farming systems of Ethiopia livestock is a very important enterprise. Farmers select crop species/ varieties not only based on grain yield but also straw yield. Similarly legumes with multiple use were more favoured by the community than those legumes that were appropriate solely for green manure purposes.

Above mentioned socio-economic criteria of farmers together with the productivity data from the field were used to develop decision guides to help farmers in selecting legumes to be incorporated into their land use systems as presented in Fig. 3. As mentioned above, farmers considered the degree of land productivity as the most important factor (placed at the highest hierarchy) for possible integration of legumes. Farmers who own degraded arable lands were willing to integrate more LCCs while those who own productive lands of large size wanted to grow food legumes with additional feed values. However, all farmers decided to have food legumes in their system regardless of farm size or land productivity. Beans and Pea are already in the system and farmers already found niches to grow them as they are also parts of the local dish. From the LCCs, farmers favoured vetch as mentioned above. Those farmers who wanted soil improving LCCs selected croletaria, as they found it better performing even under extremely degraded farms. However, about 45% the farmers with degraded arable lands are not willing to integrate LCCs, either because they did not manage their own farm, and practice share cropping /contract or have limited options of household income.

In general, given very high population pressure and associated severe land shortage, farmers in Areka may not allocate full season for LCC, but preferred fast growing LCCs for short term fallow. The probability of integrating LCCs into the system became even less when the land is relatively fertile. As the homestead fields are relatively fertile and used for intercropping/relay cropping purposes, growing LCC on that part of the land may not be the choice of farmers. On the other hand, farmers with large farm size and high degree of land degradation may go for selected LCCs. The potential niche available in the system would be the least fertile most-out field where intercropping is not practised. The most out field is commonly occupied by potato in rotation with maize with relatively less vegetative cover over the years .

The length of the growing period together with the amount and distribution of the rainfall dictates whether the system may allow growing legumes intercroped with maize, intercroped with perennials, or relay cropped with maize or sweet potato. In regions, where the growing season is extended up to eight months, and where the outfield became depleted to sustain crop production, LCCs that could grow under poor soil fertility conditions in drought-prone months would be appreciated. Indeed, crotalaria performed very well under such conditions.

3.4. The Decision Guides

We are presenting three guidelines for integration of legumes into the farming systems of multiple cropping, perennial-based systems.

The decision trees were developed based on the following back ground information from the site.

1) Farmers preferred food legumes over non-food legumes regardless of soil fertility status of their farm
2) The above ground biomass of grain legumes (grain & stover) is exported to the homestead for feed and food while the below ground biomass of grain legumes is small to effect soil fertility. The probability of the manure to be returned to the same plot is less as farmers prefer to apply manure to the perennial crops (Enset & Coffee) growing in the home stead.
3) The tested legumes may fix nitrogen to fulfil their partial demand (we have observed nodules in all although we did not quantify N-fixation), but in conditions where the biomass is exported, like vetch for feed, most of the nutrient stock would be exported. Therefore, we did not expect significant effect on soil fertility.
4) LCCs produced much higher biomass when planted as relay crops in the middle of the growing season than when planted at the end of the growing season as short-term fallows due to possible effects of end-of season drought.
5) The homestead field is much more fertile than the outfield; hence those legumes sensitive to water and nutrients will do better in the homestead than in the outfield.

Fig. 3 Guideline for integration food, feed legumes and legume cover crops in small-scale farms.

The first guide (Fig 2) is intended to assist researchers to get feed back information about technologies that were accepted or rejected by the farmers or farmer research groups. This guide will assist researchers not only to identify the major reasons for the technology to be accepted or rejected, but also to prioritise the reasons of resistance by farmers not to adopt the technology. This type of feed back will help to modify/improve the technology through consultative research to make technologies compatible to the socio-economic conditions of the community.

The second guide (Fig 3) integrated both biophysical and socioeconomic indicators. The most important criteria at the lowest level is the presence or absence of livestock in the household followed by who manages the farm, market access, the size of the land holding and the land quality. The factor that dictates the decision at the highest level was land productivity, which was governed mainly by soil fertility status. Growing food legumes was the priority of every farmer regardless of wealth (land size, land quality & number of livestock). Farmers with livestock integrated feed crops regardless of land size, land productivity and market access to products. However, the size and quality of land allocated for growing feed legumes depended on market access to livestock products (milk, butter and meat). Those farmers with good market access are expected to invest part of their income on external inputs, i.e. inorganic fertilisers. Hence farmers of this category did not allocate much land for growing LCCs, but applied inorganic fertilisers. In the homestead field, there was no land allocated for LCCs in the system, not only because farmers gave priority to food legumes, but it also became very expensive for farmers to allocate the fertile plot of the farm for growing LCCs. The most clear spatial niche for growing LCCs is the most out field, especially in poor farmers' field with exhausted land and limited market-driven farm products. Because the land of most poor house holds was on the verge of being out of production due to the iniquitous nature of land management practices through years long share cropping arrangements.

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Draft Paper

Towards Addressing Land Degradation in Ethiopian Highlands: Opportunities and Challenges

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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.

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Phosphorus use efficiency as related to sources of P fertilizers, rainfall, soil and crop management in the West African Semi-Arid Tropics

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Abstract

The rainfall of agricultural areas of the West African Semi-Arid Tropics varies from 300 to 1200 mm. Although in absolute terms rainfall is low only in the Northen half of the desert margins, the high inter-annual variability associated with eratic distribution of rainfall in space and during the growing season constitute major limitation for agricultural production. Continuous and intensive cropping without restoration of the soil fertility has depleted the nutrient base of most of the soils. For many cropping systems in the region, nutrient balances are negative, indicating soil mining. Among soil fertility factors, phosphorus deficiency is a major constraint to crop production. Phosphorus use efficiency (PUE) is defined as yield increase per kg fertilizer P added, is related to P sources, environmental factors, soil and crop management.

In addition to water soluble P fertilizers, PR sources from Niger (Parc - W PR and Tahoua PR), Mali (Tilemsi PR) and Burkina Faso (Kodjari PR) and modified partially acidulated phosphate rocks (PAPR) effect on P-use efficiency is reported. PAPR improved the PUE of PR sources. Among the four PR sources in the region, Tahoua PR (TPR) recorded highest PUE as compared to Kodjari (KPR) or Parc-W (PRW) sources.

Rainfall received in September at grain filling and maturation stage was best correlated to PUE. There is large difference in PUE of different pearl millet cultivars and values varied from 25 to 77 kg grain. Kg P^{-1}.

The hill placement of 4 kg $P.ha^{-1}$ at planting time improved the PUE as compared to present recommendation of 13 $kg.ha^{-1}$ broadcast and also improved the efficiency of phosphate rock.

The rotation of cereals and cowpea and soil amendment with crop residue application increase drastically the PUE in the region.

Key words : P use efficiency, rainfall, soil and crop management, Pearl millet, Cowpea, West Africa

I. Introduction

The West African Semi-Arid Tropics is the home of the world's poorest people, 90% of whom live in villages and depend for their livelihood on subsistence agriculture. In this zone, the length of crop growing season ranges from 75 to 150 days. Recurrent droughts, soils of poor native fertility, wind erosion, surface crusting and low water-holding capacity are the main abiotic constraints to crop production.

In traditional agricultural systems, when crop yields declined to unacceptable levels, over-cropped land was left to fallow until soil fertility was built up, and new land was opened for cultivation. Increasing population pressure is decreasing the availability of land and is leading to reduce duration of fallow relative to the duration of cropping. As a result, shifting cultivation is losing its effectiveness and soil fertility is rapidly declining in many areas. The present farming systems are unsustainable without external inputs of nutrients, will continue to be low in productivity and have long-term destructive potential to the environment. In such systems, plant nutrient balances are negative (Stoorvogel and Smaling, 1990).

Among soil fertility factors, phosphorus deficiency is a major constraint to crop production and response to nitrogen is substantial only when both moisture and phosphorus are not limiting (Traoré, 1974). Although lack of water limits crop production in the drier zones in the Sahel, all available evidences indicates that inherent low fertility (mainly P) is a more serious problem (Breman and de Wit, 1983; van Keulen and Breman, 1990).

For many years, research has been undertaken to assess the extent of soil phosphorus deficiency, to estimate phosphorus requirements of major crops, and to evaluate the agronomic potential of various phosphate fertilizers including phosphate rock (PR) from local deposits (Goldsworthy, 1967a and 1967b; Pichot and Roche, 1972; Thibaut et al., 1980; Bationo et al., 1987; Bationo et al., 1990).

In a survey of the fertility status of representatives sites, Manu et al. (1991) found that the total P in these soils ranged from 25 to 349 mg kg^{-1} with a mean of 109 mg kg^{-1}. Available P with Bray P1 was also generally low, ranging from 1 to 30 mg kg^{-1} with an average of 6 mg kg^{-1}. However, 77% of samples had available P values of less than 8 mg kg^{-1} which has been determined to be the critical P level required to obtain 90% of the maximum pearl millet yield in the sandy soil of Niger (Bationo et al., 1989a).

The method of Fox and Kamprath (1970) was used to study the P-sorption characteristics of those soils and selected adsorption isotherms are presented in Figure 1. Sorption data were fitted to the Langmuir equation (Langmuir, 1918) and phosphorus adsorption maxima were calculated. From these representative sites, Manu et al., (1991) found that the values of maximum P sorbed ranged from 27 mg kg^{-1} to 253 mg kg^{-1} with a mean of 94 mg kg^{-1}. Soils of this region can be considered as having relatively low P sorption capacities compared to clay rich Utisols and Oxisols found in humid tropical regions (Sanchez and Uehera, 1980). As a consequence of the low P retention capacity of these soils, relatively small quantities of P fertilizers will be needed for optimum crop growth.

Phosphorus use efficiency in this paper is calculated by dividing the difference in yield between P-treatment and control with the rate of P applied. In addition to the water soluble P sources such as single superphosphate (SSP) and triple superphosphate (TSP), phosphate rocks (PRs) indigenous to this region such as Tahoua PR (TPR) and Parc-W PR (PRW) from Niger, and Kodjari PR (KPR) from Burkina Faso were evaluated in field trials on the main soil types for crop production. In this region, use of water soluble imported P fertilizers is severely limited because of their high cost. The direct application of PR indigenous to the region may be an economical alternative to the use of more expensive imported P fertilizers. Some PRs may not be suitable for direct application because of their low chemical reactivity (Hammond et al., 1986). Partial acidulation of PR (PAPR) represents a technology that improves the agronomic effectiveness of an indigenous PR at a lower cost than would be required to manufacture the conventional, fully acidulated fertilizers from the same rock (Chien and Hammond, 1978; Hammond et al., 1986; Bationo et al., 1990).

In this paper, after a brief review of the phosphorus use efficiency (PUE) of crops as effected by sources of P fertilizers, we will discuss the effect of rainfall, crop and soil management on Phosphorus use efficiency (PUE).

Materials and methods

A) Effect of P sources and rainfall on PUE

Experiment on the evaluation of different sources of P fertilizers.

From 1982 a benchmark field trial was initiated on the Sandy Sahelian soils of ICRISAT at Sadoré to evaluate the agronomic efficiency of different sources of P fertilizers. The sources of P fertilizers in those trials were Parc W phosphate rock (Parc W PR), Partially acidulated rock Parc W at 50 % (Parc W PAPR), Triple Superphosphate (TSP), and Single superphosphate (SSP). P was applied at 0, 4.8, 8.8, 13, 17.6 $kg.ha^{-1}$. Pearl millet cultivar CIVT was used as test crop.

Experiment on PUE efficiency in different agro-ecological zones.

In 1996 field trials were conducted at Sadoré, Gobery and Gaya to evaluate the agronomic effectiveness of Kodjari PR (KPR) and Tahoua PR (TPR) compared to single superphosphate (SSP).

Experiment on the effect of soil and crop management on PUE

Experiment on placement of P fertilizers

In a researcher managed trial at Karabedji, hill placement of small quantities of fertilizers were evaluated on water soluble and phosphate rock on pearl millet and cowpea. The two PR used were Tahoua phosphate rock (TPR) and Kodjari phosphate rock (KPR).

Effect of mineral and organic fertilizers, ridging, and rotation of pearl millet and cowpea on PUE.

In 1998 data were collected in an experiment to evaluate the effect of nitrogen application, crop residue, ridging and rotation of pearl millet with cowpea on PUE.

Effect of rotation on PUE

From 1992 to 1995 an experiment was conducted to study the effect of crop rotation of pearl millet and cowpea on PUE at the ICRISAT Sahelian Center. Phosphorus was applied at 0, 6.5 and 13 $kg.ha^{-1}$ as single superphosphate.

Results and discussion

Phosphorus use-efficiency as related to different sources of P fertilizers and rainfall

For the benchmark experiment was conducted during the period of 1982-1987 SSP outperformed the other sources and its superiority to sulfur-free TSP indicates that with continuous cultivation, sulfur deficiency develops (Frisen, 1991). For both pearl millet grain and total dry matter yields, the relative agronomic effectiveness was almost similar for TSP as compared to PAPR with 50% acidulation (PAPR50) indicating that partial acidulation of PRW at 50% can significantly increase its effectiveness (Figure 2). SSP had the highest PUE values at all rates of P application. Increased rate resulted in a decrease in PUE. For pearl millet grain, application of 4.4 kg P/ha resulted in a PUE of 100 kg grain/kg P, but the PUE decrease to 45 kg grain/kg P at the rate of application of 13 kg P/ha. The difference between the P sources is better resolved at lower application rates of P fertilizers as compared to the higher application rates. The difference between PRW and SSP at 4.4 kg P/ha was 50 kg grain/kg P while at 17.5 kg P/ha, this difference was reduced to only 27 kg grain/kg P (Figure 2).

For the trial for agronomic evaluation of P sources in different agro-ecological zones of Niger, the response of pearl millet to different sources of P fertilizers indicates that TPR agronomic effectiveness outperformed KPR (Figure 3 and Table 1). These results are in agreement with the fact that the molar PO_4/CO_4 ratio is 23.0 for KPR and 4.88 for TPR, and TPR also has a higher solubility in NAC. Mokwunye (1995) found that the level of isomorphic substitution of carbonate for phosphate within the lattice of the apatite crystal influences the solubility of the apatite in the rock and therefore controls the amount of phosphorus that is released when PR is applied to soils. Chien (1977) found that the solubility of PR in neutral ammonium citrate (NAC) was directly related to the level of carbonate substitution. As a result of the higher value of Tilemsi PR in NAC, and the high substitution of carbonate for phosphate, Bationo et al. (1997) found that Tilemsi PR can result in net returns and value/cost ratios similar to recommended cotton or cereal complex imported fertilizers.

The PUE at Gobery was 31 kg grain/kg P for TPR, but decreased to 9 kg grain/kg P with KPR application at 17KgP/ha. As soils in Gaya and Gobery are more acidic and receive more rain than the Sadoré site, the agronomic effectiveness is higher at those sites. The ability of the soil to provide the H^{+} ions is essential to ensure the effectiveness of PR to crops (Chien, 1977; Khasawneh and Doll, 1978). Therefore, acidic soils with a high pH buffering capacity provide an ideal environment for PR dissolution. Results presented for upland rice by Bado et al., 1995 indicate that PUE of the unreactive Kodjari PR on an acidic (PH in $H_20 = 5$) soil is similar to the PUE of the water soluble TSP (Mahaman et al., 1998).

The agronomic effectiveness of the leguminous cowpea is not better than the cereal pearl millet crop (Table 1). This is in contradiction to others reports where legumes have higher strategy to solubilize

PR than cereal by rhizosphere acidulation (Aguilar and van Diest, 1981; Kirk and Nye, 1986; Hedley et al., 1982) and exudation of organic acids (Ohwaki and Hirata, 1992).

The increase in soil pH resulting from flooding of rice fields is expected to depress the dissolution of PR. Enhanced performance of PR in flooded systems has been reported (Hammond et al., 1986). Kirk and Nye (1986) explain the enhance PR performance in flooded soils by arguing that rice roots will acidify surrounding soil and that dissolved organic matter may chelate Ca and P. In the irrigated system the PUE of PR often was higher than TSP (INRAN, 1988).

Using data of PUE at 13 kg P ha^{-1} details from experiment presented in Figure 2 conducted over 10 years period, it was found that the rainfall received in September at grain filling and maturation stage was best correlated to PUE (Figure 4). From the results presented in Figure 4, it could be concluded that PUE of SSP was most affected by the amount of September rainfall due to its higher biomass production as compared PR or PAPR50. The predictions indicate that for SSP, a 40 mm rainfall in September will result in a PUE of 118 kg dry matter/kg P while for 100 mm rainfall the PUE will increase to 160 kg dry matter/kg P.

In the West African Semi-Arid Tropics, both water and nutrients limits crop production, but from multi-location water-balance studies in Niger, it was shown that an important outcome of fertilizer use is an increase in water-use efficiency (Breman and de Wit, 1983; van Keulen and Breman, 1990). In long-term experiments, water-use efficiency (WUE) for grain yield increased dramatically from 5.4 kg mm^{-1} ha^{-1} without the use of fertilizers to 14.4 kg mm^{-1} ha^{-1} with the use of fertilizers. Increased root growth due to P application is associated with greater rooting depth and deeper extraction of moisture during dry spells (Payne and al., 1995). Early vigor and enhanced growth due to P application results in more complete ground cover early in the season, which reduces the proportion of water lost through water evaporation to some extent, thus facilitating effective and efficient use of rainfall.

Although the application of fertilizers improves WUE, the efficiency of fertilizer depends on the amount of rainfall received by the crop. For nitrogen, Bationo et al. (1989b) developed a model relating grain yield of pearl millet to mid-season rainfall (45 days, from mid-July to end of August). This model predicts that response to N in dry years will be limited, with little benefit to the farmers from the investment in N fertilizers.

b) Relationship between crop and soil management on phosphorus use efficiency

Over a period of three years, nine pearl millet cultivars were evaluated to determine their PUE. For both grain and stover, there are very large differences among the nine cultivars for their response to the application of P fertilizer (Figure 5). PUE at 13 kg P ha^{-1} varied among the 9 cultivars from 25 kg grain/kg P for variety ICMV IS 85333 to 77 kg grain/kg P for Haini-Kirei cultivar the local is 3 weeks later to mature and has a very dense root system. Figure 6 shows PUE of different genotypes was significantly correlated with grain yield at 13 kg P ha^{-1} was, and explained 77% of total variation in this relationship. This significant relationship indicates that phosphorus use efficient cultivars can be first identified using their grain yield performance at 13 kg P/ha. The relationship between the PUE of the different genotypes with grain yield in the absence of P application was not significant and only 15% of the total variation could be explained. This observation shows that a cultivar with a high PUE coefficient will not necessarily perform better under low P conditions than the one with a low PUE coefficient. This also implies that genotypes selected for high grain yield under low-P situations will not necessarily be P-use efficient. There is ample evidence that indicates marked differences exist between species and genotypes for P uptake (Föhse et al. 1988; McLachlam, 1976; Caradus, 1980; Nielsen and Schjorring, 1983; Spencer et al. 1980).

For the researcher managed on-farm trials conducted to study interaction between hill placement of small quantities of P fertilizers on the efficiency of water soluble (SSP, 15-15-15) and phosphate rock (PRT and PRW). Results presented in Table 2 and 3 indicate that hill placement increases the agronomic effectiveness of both water soluble and PR sources for pearl millet and cowpea. Compared to the control, the pearl millet grain yield increased from 281 to 1493 kg ha^{-1} respectively, for the control and the 15-15-15 broadcast plus 15-15-15 hill placed treatments whereas the application of only 15-15-15 yielded 661 kg/ha. The PUE results in Table 3 indicate that hill placement of 4 kg P ha^{-1} with broadcast PRK can improve the PUE of the unreactive PRK. For cowpea fodder, PUE increased from 44 kg/kg P with the addition of KPR only to 93 when KPR is broadcast with hill placement of 15-15-15 (Table 3). Whereas PUE efficiency is 14 for pearl millet grain yield with KPR broadcast it increased to 31 kg grain/kg P when additional hill placement for 15-15-15 is applied (Table 2). Although hill placement alone of 4 kg P ha^{-1} gave high PUE values as compared to broadcast of 13 kg P ha^{-1}, this treatment will result in a net negative P balance. With the association of hill placement and low cost PR sources the net balance of P will be positive and soil mining will be avoided. For most of cases, 15-15-15 hill placement efficiency is higher than SSP hill placement. This is due in part to germination failures most likely due to deleterious pH and salt effects on the seedling. The highest effectiveness of NPK placement is also likely due to a stimulation of early root growth by the ammonium component (Marschner et al., 1986), and an enhanced availability of P in the immediate seedling environment. Over the past few years, on-station research at ICRISAT-Niger has focussed on the placement of small quantities of P fertilizers at planting stage in order to develop optimum farmer-affordable P application recommendation. Compared to control, millet grain yield increased between 60 to 70% when 5 kg P ha^{-1} was hill placed, and by 100% when 13 kg P ha^{-1} was broadcast. PUE on total dry matter and grain yield indicate that PUE at 3,5 and 7 kg P ha^{-1} hill application was higher as compared to broadcasting 13 kg P/ha. For example, in 1995, for total dry matter, the PUE for 13 kg P/ha was 159 kg TDM/kg P as compared to 402 kg TDM/kg P with the application of 3 kg P/ha hill placed. This is due in part to the placement of P where the soil is humid as compared to the surface broadcast where some fertilizers will remain in the dry zone of the soil (Muhelhig-Versen et al., 1997).

In long-term soil management trials, application of nitrogen, crop residue and ridging and rotation of pearl millet with cowpea were evaluated to determine their effect on PUE. The results show that soil productivity of the sandy soils can be dramatically increased with the adoption of improved crop and soil management technologies. Whereas the absolute control recorded 33 kg ha^{-1} of grain, 1829 kg ha^{-1} was obtained when phosphorus, nitrogen and crop residue were applied to plots that were ridged and followed leguminous cowpea crop the previous season (Table 4). Results indicate that for grain yield, PUE will increase from 46 with only P application to 133 when P combined with nitrogen and crop residue applications and the crop is planted on ridge in a rotation system.

In a study on the long-term effect of different cropping systems on PUE it was found that rotation of pearl millet with cowpea could significantly increase pearl millet and cowpea production (Figure 7). For pearl millet total dry matter, PUE increased from 149 kg ha^{-1} in the continuous cultivation to 252 kg ha^{-1} in rotation systems. For cowpea fodder, PUE increased from 40 kg ha^{-1} in the continuous cultivation to 65 kg ha^{-1} with rotation.

In a long-term field trials to study the effect of crop residue application on PUE, PUE was 67 kg/kg P when only P fertilizers were applied, its value doubled when P fertilizers were combined with crop residue (Bationo et al., 1985).

Conclusion

In the West African Semi-Arid Tropics, lack of volcanic rejuvenation has caused the region to undergo several cycles of weathering erosion, and leaving soil poor in nutrients.

Both total and available P values are very low and P deficiency is a major constraint to crop production. With their sandy texture, these soils have low P retention capacity.

The PUE is highly variable and depends on P sources, rainfall, soil and crop management. In the West African Semi-Arid Tropics there is little research on understanding the factors affecting P uptake such as the ability of plants to i) solubilize soil P through pH changes and the release of chelating agents and phosphates enzymes, ii) explore a large soil volume, and iii) absorb P from low soil solution P concentration.

Genotypic improvement can come through increased capacity of plants to extract P from the soil or for decreased internal P requirement per unit dry matter produced. The opportunities for increased efficiency of P utilization through cultivar improvement include selection for treatments that favor strong plant demand such as late maturity, increased rootlet activity and increased P solubilization capacity.

The available and total P values are very low in the region. With those extremely low values of total P, it can be questionable to select cultivar adapted to low P condition, as one cannot mine what is not there. Direct application of indigenous PR can be an economic alternative to the use of more expensive imported water-soluble P fertilizers.

The effectiveness of mycorrhizae in utilizing soil P has been well documented (Silberbush and Barber, 1983; Lee and Wani, 1991, Daft, 1991). An important future research opportunity is the selection of plant genotypes that are conducive to colonization by efficient Vesicular-Arbuscular Mycorrhizal (VAM) associations for better utilization of P from PR.

Previous agronomic research has already identified a significant number of technologies to enhance PUE but future research needs to screen technologies under farmer's management in order to recommend with the highest economic returns.

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Table 1: Relative agronomic effectiveness for pearl millet and cowpea as compared to SSP (%) Of Tahoua phosphate rock (TPR) and Kodjari phosphate rock (KPR) in three agro Ecological zones of Niger

	Sadore		Goberi		Gaya	
	TPR	KPR	TPR	KPR	TPR	KPR
Grain yield (kg/ha)	63	32	76	41	80	57
Total biomass (kg/ha)	65	35	60	40	68	63
Cowpea fodder (kg/ha)	43	28	73	51	42	42
Cowpea total dry matter (kg/ha)	56	40	72	51	52	55

Table 2: Effect of different sources* and placement of P on pearl millet yield and PUE, Karabedji, 1998 rainy season**

P Sources and method of application	Grain		TDM	
	Yield (kg ha^{-1})	PUE	Yield (kg ha^{-1})	PUE
Control	281		1726	
SSP broadcast*	535	23	3726	154
SSP broadcast + SSP HP**	743	27	5563	226
SSP HP	611	83	3774	514
15-15-15 broadcast	660	29	4226	192
15-15-15 broadcast + 15-15-15 HP	1493	71	7677	350
15-15-15 HP	690	102	4767	760
PRT broadcast	690	31	4135	185
PRT broadcast + SSP HP	663	22	4365	155
PRT broadcast + 15-15-15 HP	806	31	5061	196
PRK broadcast	465	14	3302	121
PRK broadcast + SSP HP	747	27	5052	196
PRK broadcast + 15-15-15 HP	806	31	5010	193
S.E	84		194	

PUE Kg grain/KgP; HP Hill Placed; TDM Total Dry Matter
**For broadcast, 13 KgP/ha was applied *For HP, at 4 KgP/ha SSP Single superphosphate; 15-15-15 compound fertilizer containing 15% N, 15% P_2O_5, 15% K_2O; TPR Tahoua Phosphate Rock; KPR Kodjari Phosphate Rock

Table 3: Effect of different sources* of phosphorus and their placement on cowpea yield and PUE, Karabedji, 1998 rainy season**

P Sources and method of application	Grain		Fodder	
	Yield (kg ha^{-1})	PUE	Yield (kg ha^{-1})	PUE
Control	505		1213	
SSP broadcast	1073	44	2120	70
SSP broadcast + SSP HP	1544	61	3139	113
SSP HP	1050	136	2021	452
15-15-15 broadcast	1165	51	2381	90
15-15-15 broadcast + 15-15-15 HP	2383	110	3637	142
15-15-15 HP	1197	173	2562	337
PRT broadcast	986	37	2220	77
PRT broadcast + SSP HP	1165	68	3127	113
PRT broadcast + 15-15-15 HP	1724	72	3163	115
PRK broadcast	920	32	1791	44
PRK broadcast + SSP HP	1268	45	2588	81
PRK broadcast + 15-15-15 HP	1440	55	2792	93
S.E	*164*		*313*	

PUE Kg grain/KgP; HP Hill Placed; TDM Total Dry Matter
**For broadcast, 13 KgP/ha was applied ** For HP, at 4 KgP/ha
*SSP Single superphosphate; 15-15-15 compound fertilizer containing 15% N, 15% P_2O_5, 15% K_2O; TPR Tahoua Phosphate Rock; KPR Kodjari Phosphate Rock

Table 4: Effect of mineral fertilizers, crop residue (CR) and crop rotation on pearl millet yield and PUE, Sadore, Niger, 1998 rainy season.

Treatment	Without CR, without N				Without CR, with N				With CR, without N				With CR, with N			
	TDM		Grain		TDM		Grain		TDM		Grain		TDM		Grain	
	Yield	PUE	Yield	PUE	Yield	PUE	Yield	PUE	Yield	PUE	Yield	PUE	Yield	PUE	Yield	PUE
Control	889		33		2037		58		995		61		1471		98	
13 kg P/ha	2704	140	633	46	4339	177	1030	75	4404	185	726	51	240	4594	1212	86
13 kg P/ha + ridge	2675	137	448	32	4057	155	946	68	3685	210	785	56	4530	235	1146	81
13 kg P/ha + rotation	5306	340	1255	94	6294	327	1441	106	5392	338	1475	109	6124	358	1675	121
13 kg P/ha + ridge + rotation	5223	333	1391	104	5818	291	1581	117	6249	404	1702	126	7551	468	1829	133
SE	407		407		407		407		407		407		407		407	

CR Crop Residue; N Nitrogen; TDM Total Dry Matter; PUE (kg grain/kgP); Yield (kg/ha)

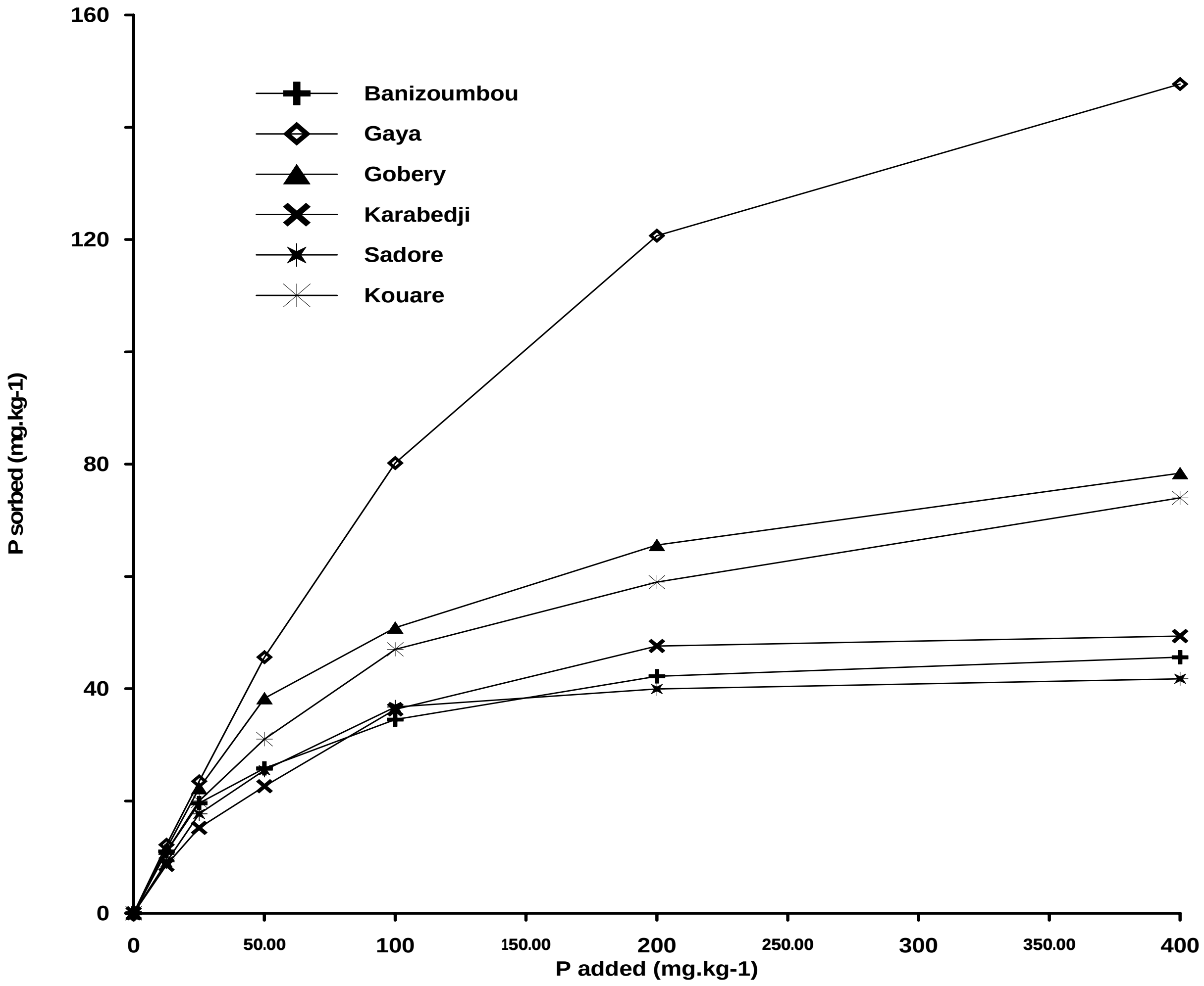

Figure 1: Phosphorus sorption isotherms of soils samples from six benchmark sites in West Africa (Niger and Burkina Faso).

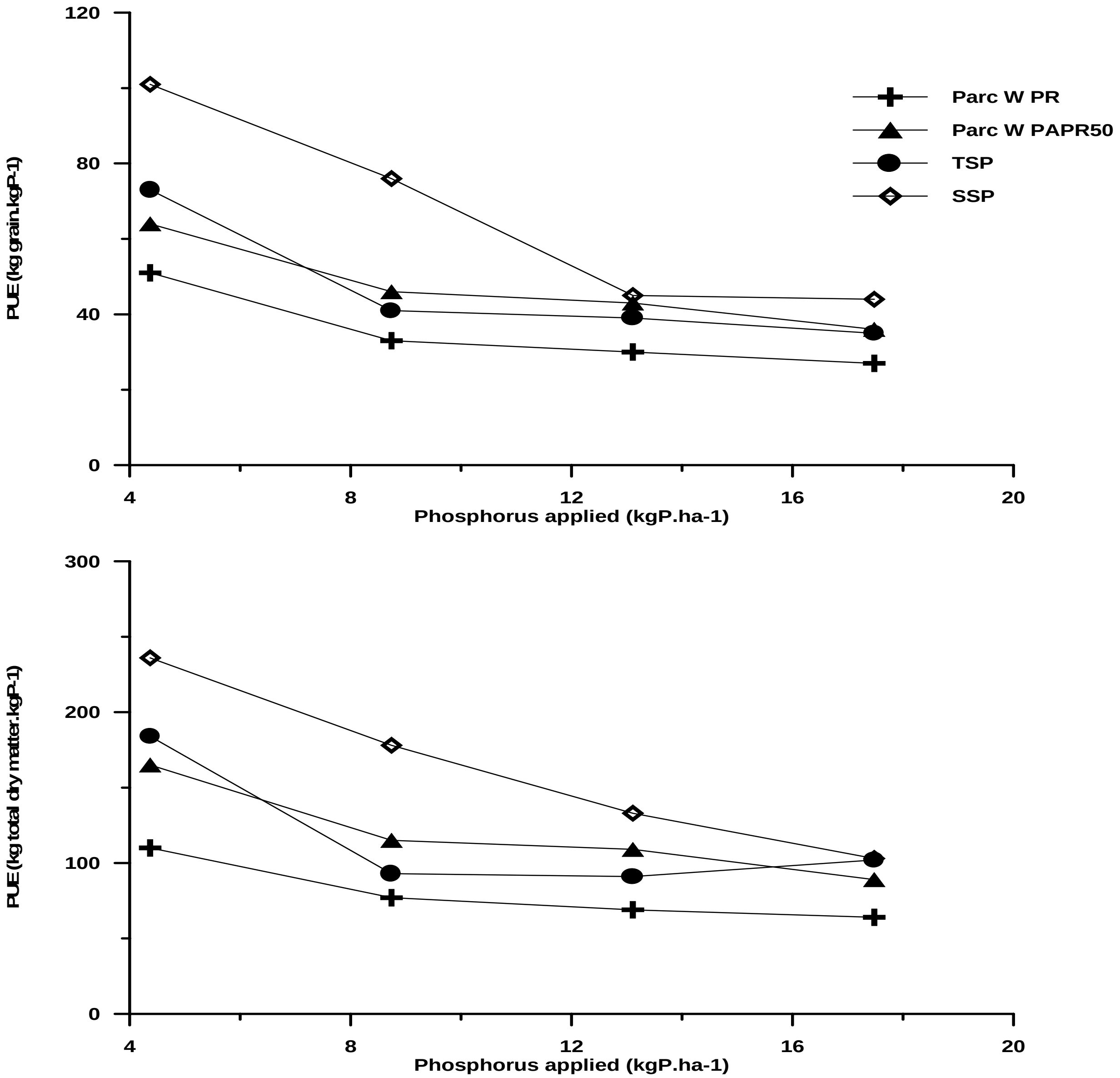

Figure 2: Relationship between different P sources and rates and PUE for pearl millet grain and total dry matter yields, rainy season, Sadoré, Niger, Average of six years data (1982 to 1987).

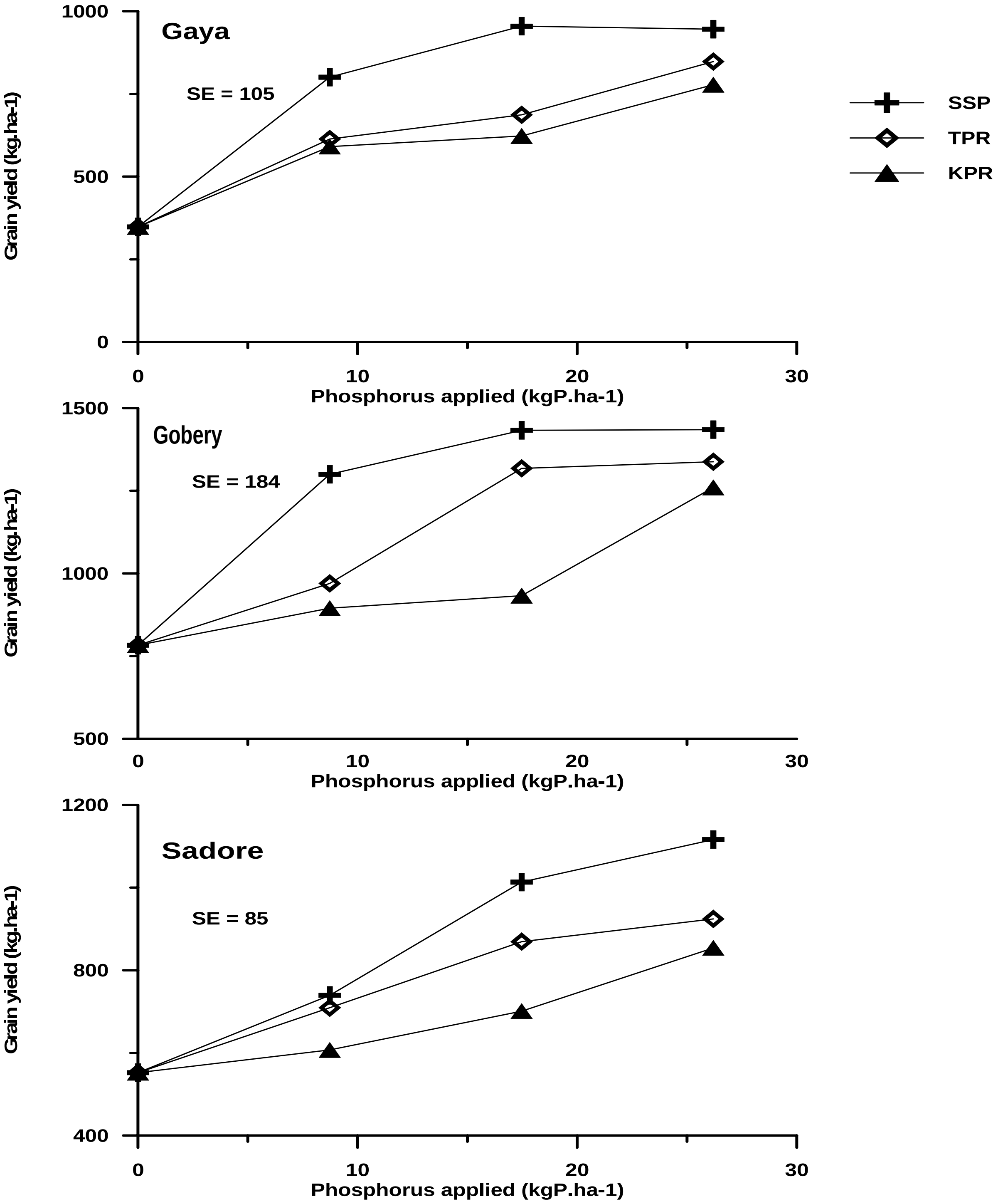

Figure 3: Relationship between P sources and rates on pearl millet grain yield in three agro-ecological zones of Niger, 1996 rainy season.

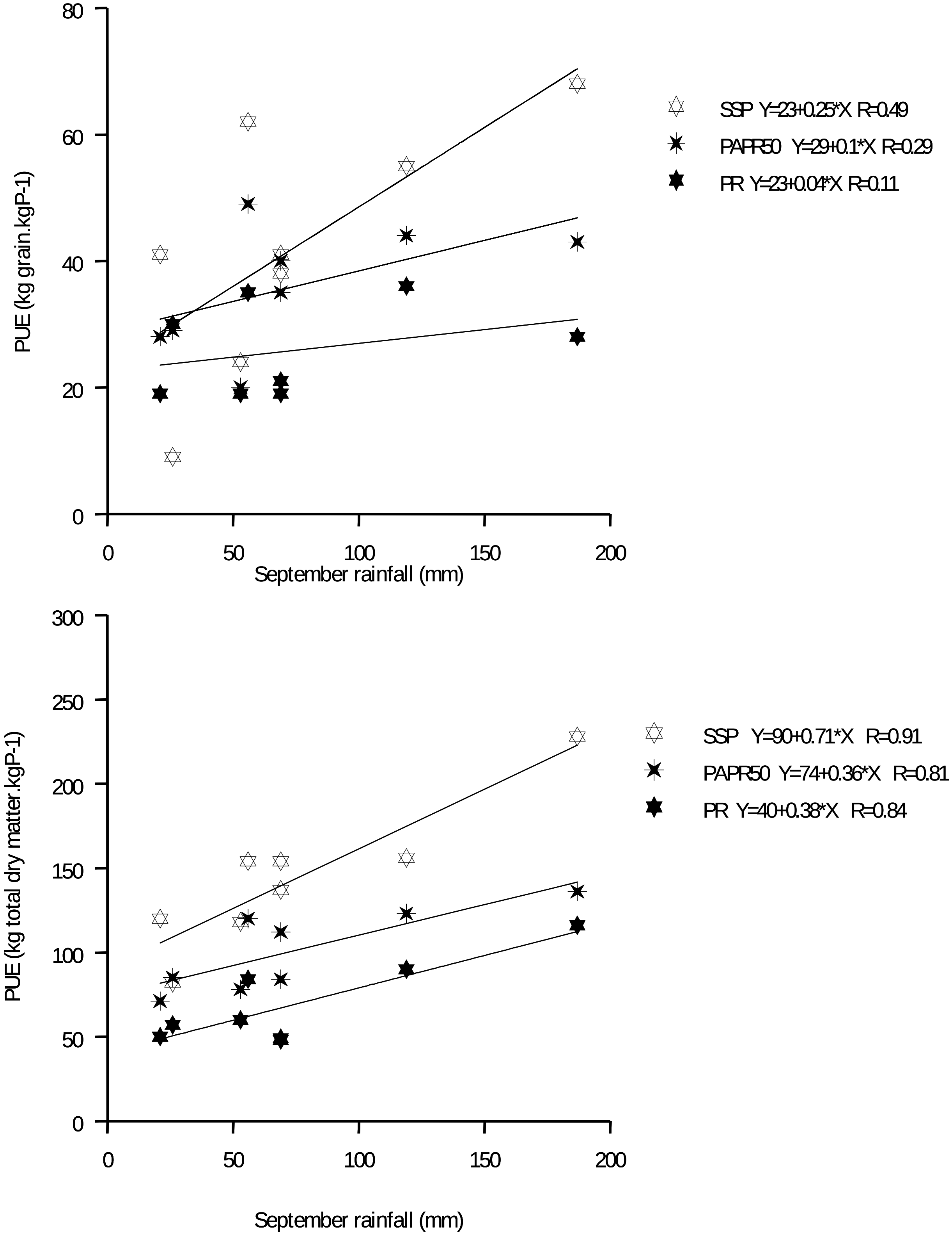

Figure 4: Relationship between September rainfall and PUE for pearl millet grain yield and total dry matter, Sadoré, Niger, 1982-1993 rainy seasons.

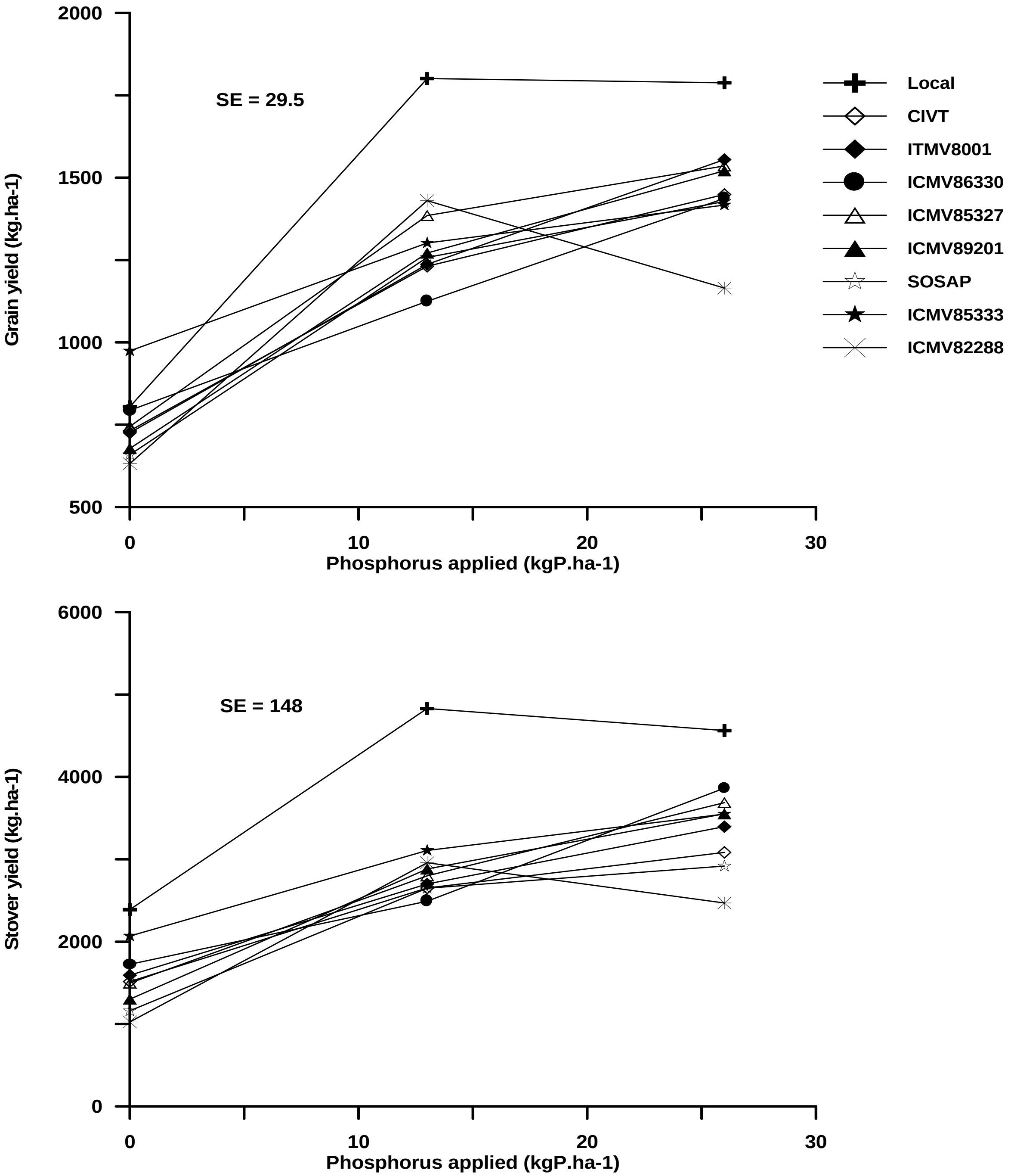

Figure 5: Relationship between phosphorus applied and grain and stover yields for nine pearl millet cultivars, Sadoré, Niger, rainy season 1991-1993

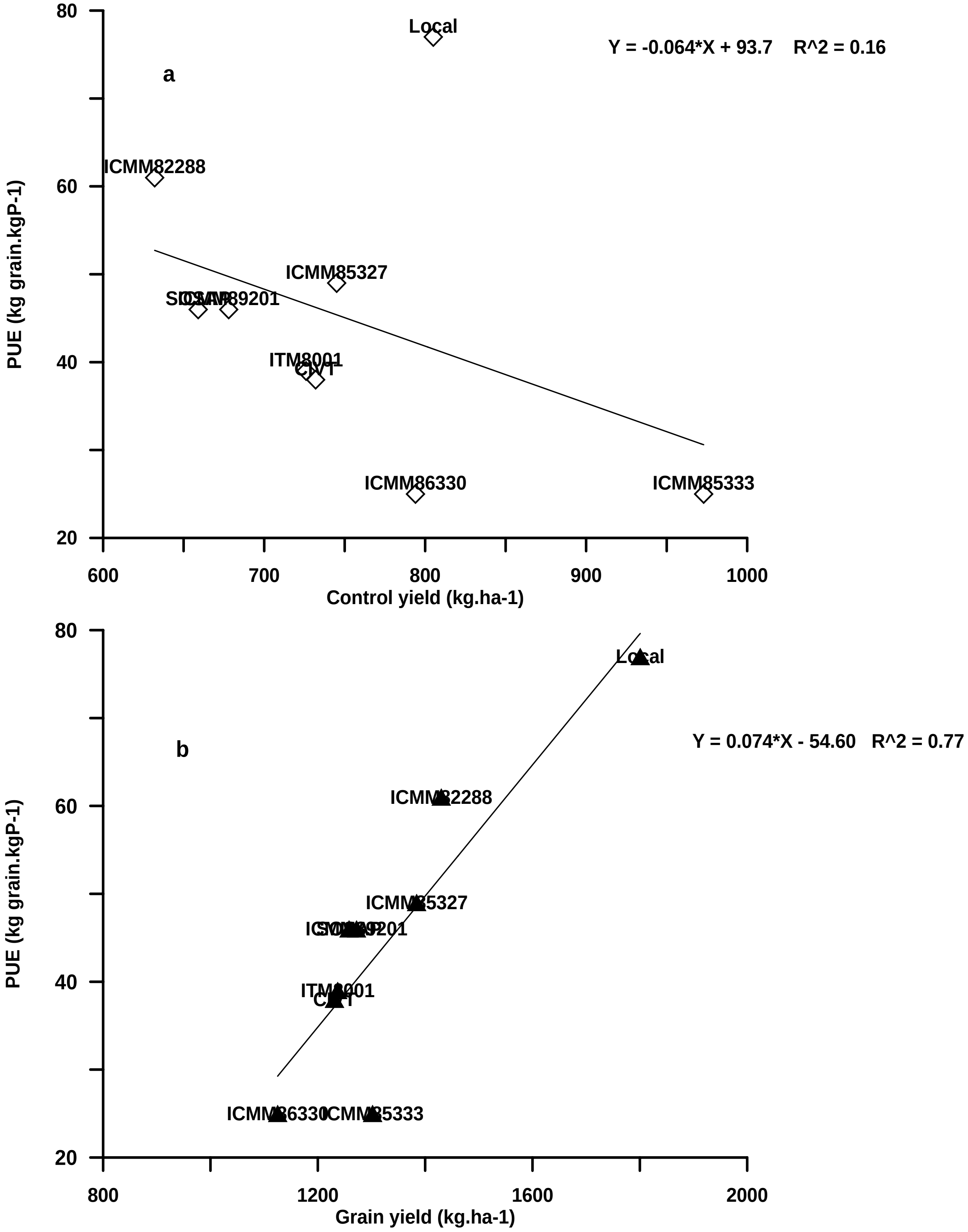

Figure 6: Relationship between PUE at an application rate of 13 kg P/ha and grain yield of unfertilised (a) and fertilised (b) millet.

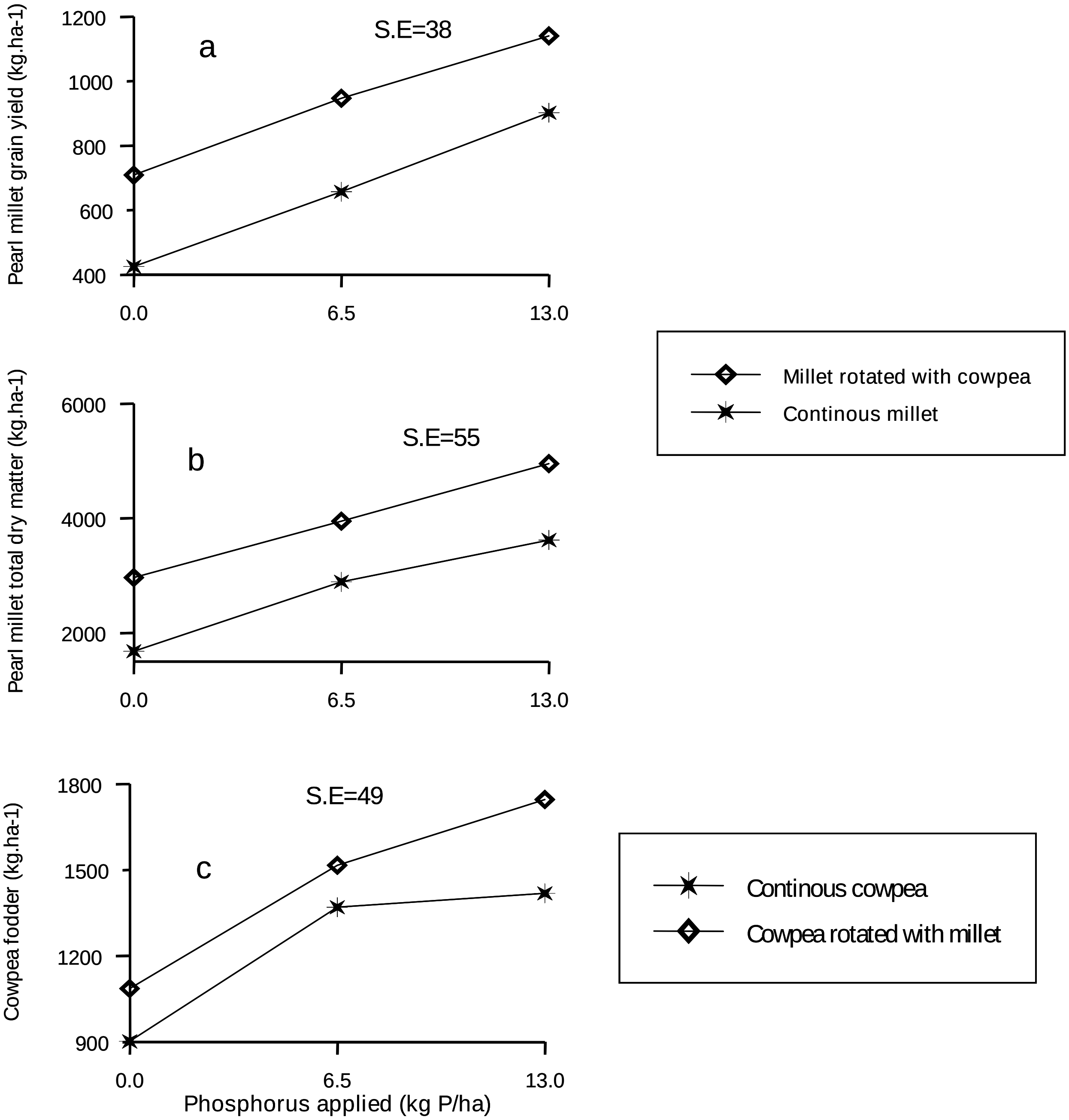

Figure 7: Effect of phosphorus and cropping systems on pearl millet grain (a), total dry matter (b), and cowpea fodder (c) yields, Sadoré, Niger, rainy season 1992-1995.